SOME EXTENSIONS TO
IRVINE DATA FLOW LANGUAGE (Id)

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MASTER OF TECHNOLOGY

By
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CERTIFICATE

This is to certify that the thesis entitled "SOME EXTENSIONS TO IRVINE DATA FLOW LANGUAGE (Id)" by Vinod Kumar Kathail has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Data flow languages are gaining importance because of their inherent asynchronous view of computation. Some extensions to the high-level data flow language Id (Irvine data flow language) are proposed to increase its effectiveness and expressive power. The proposed extensions are in accordance with the recent advances in the area of programming language design and programming methodology. Sequential and mixed looping constructs are proposed which alongwith the existing parallel looping construct and with the proposed incorporation of generators provide a comprehensive and flexible set of looping constructs. Stream structures are proposed to model the arrays of streams. Their usefulness in the resource management to maintain a variable number of queues is discussed. To aid in program abstraction and to enable a programmer to define his own language, tailored to his needs, programmer defined constructs (pdcs) are incorporated. The approach used to incorporate programmer defined constructs has some similarities with the well known conditional assembly of macros used in low level languages. Usefulness and implementation of some of these aspects in conventional languages is briefly discussed.

CHAPTER 1

INTRODUCTION

1.1 Objective

Dataflow languages are gaining importance because of their inherent asynchronous view of computation and thus their ability to act as a suitable semantic basis for parallel computation. The objective of this thesis is to propose some extensions to a higher-level dataflow language Id [AGP78] (Irvine dataflow language) developed by the Dataflow Architecture Group at University of California, Irvine. Proposed extensions enhance the capabilities of Id looping constructs, provide a general model to maintain a large and variable number of queues to deal with the problems of resource management, and enable a programmer to define his own higher level constructs using available Id schemas. Our proposed extensions should be viewed in the context of the recent advances in programming language design and programming methodology some of which are briefly discussed in Section 1.3. A reader who is familiar with the dataflow languages, their advantages over conventional languages, and Id may skip rest of this chapter and the next chapter.

1.2 Conventional languages vs dataflow languages and dataflow concepts

With the speed of semiconductor devices reaching their limits due to electrical propagation delays, parallel computation has emerged as the only basis to speed up computation to solve large and complex problems. Many computer systems like ILLIAC IV, CDC STAR-100, CRAYI etc. have been built todate to exploit the power of parallel computations. However, they are still based on conventional Von Neumann architecture[*] characterized by sequential control and memory cells, and thus require either complex software or hardware mechanisms to bring out the parallelism in the program. A new dimension is added to the problem by the recent advances in LSI technology. Large numbers of inexpensive processors are now available and thus "distributed processing" among many distinct processors with essentially autonomous control is gaining favour. However, it is now widely recognized that under the constraints of conventional architecture and languages it is extremely difficult to efficiently utilize a large number of processors, since sequential control inhibits asynchronous behaviour and existence of memory potentially requires proper synchronization of accesses to each memory cell [Den 73, GIMT 74, Wen 75, SM 77, AG 77b, AG 77c etc.]. In past many control primitives for parallel computation (CALL and WAIT

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[*] Conventional architecture and conventional languages are used interchangably as languages reflects the characteristics of architecture.

in PL/I, Cobegin-coend etc.) and synchronization schemes (Semaphores[Dij 68] etc.) have been proposed as extensions to conventional languages. However, program written using these constructs are limited in the degree of parallelism they exhibit. Thus to exploit the capabilities provided by recent technological advances, we need an asynchronous view of computation.

Dataflow languages have been proposed to give such a view of computation[Den 73, GIMT 74, AG 77b, AGP 78 etc.].They are based on the observation that an operation should be executed as soon as its input operands are available. The attractiveness of dataflow schemas as the semantic basis of parallel computation lies in two properties:

1. an instruction executes when and only when all operands needed for that instruction become available;
2. instructions at whatever level they might exist are purely functional in nature and produce no side effects i.e. there is no memory in conventional sense [AG 77b, Den 73].

Thus dataflow program is a set of partially ordered operations on operand values where the partial ordering is determined solely and explicitly by the need for intermediate results. Dataflow languages offer several advantages [Den 73, KOS 73, AG 77b, AGP 78] over conventional programming

languages such as absence of variables, highly modular
program structure and inherently functional nature. Thus
they are well suited to describe and implement asynchronous
behaviour required by many complex systems such as operating
systems. Several dataflow languages and schemas [Den 73,
KOS 73, Bah 72, KM 66 etc.] have been proposed. In
particular dataflow language proposed by Dennis [Den 73] is
well suited as a base language for a dataflow machine. Recent
efforts have been in the direction of developing higher
level languages so that dataflow becomes an attractive alter-
native for the end users. Weng [Wen 75] proposed a Textual
Dataflow Language which incorporates recursive schemas and
streams. Kasinski [Kos 73] and Bryant [Bry 77] have also
proposed languages based on dataflow concepts. Recently
Hankin etal [HOS 78] have proposed a language CAJOLE which
is still in a developmental stage. However, it allows the
programmer to define his own new constructs. Dataflow
Architecture group at University of California, Irvine has
proposed a higher level dataflow language Id and a computer
architecture suitable for its execution [AGP 78, AG 78].
Id is of a more advanced nature and incorporates ideas of
streams, monitors, nondeterministic programming, abstract
data types and operator extensiality. In this thesis we
will look at some of these features of Id more carefully.

1.3 Programming languages in general

In recent years production of reliable software has drawn a lot of attention. It has been noted that conventional languages are not well suited for program verification and for writing reliable complex software systems. Structured programming has been proposed to bring order and structure in the otherwise chaotic world of programming languages [Bac 78]. It is now well understood that development and maintenance of complex software systems is facilitated by the preservance of the problem structure in its solution and by modularization, to localize the subsequent modifications. Drive is towards a functional view of computation rather than a procedural view. Current interest in data abstraction and control abstraction [LSAS 77, SWL 77] points in this direction. To aid the verification of programs, the structure of looping constructs is being studied. It has been proposed that initialization of loop variables, loop terminating conditions and incrementation of loop variables should be explicitly stated and grouped to aid in program verification [Pra 78]. Languages whose semantics is more closely akin to mathematics have been proposed to simplify program verification [Gut 77, AW 77].

Another area which is being extensively explored, concerns with the linguistic aspects of the problems related

to resource management [JL 76]. A higher level language
especially a language suitable for distributed processing
should have capabilities to handle hardware and software
resources. Here also we see a drive towards more encapsulated
and functional approach (semaphores [Dij 68] to monitors
[Hoa 74]).

With the Backus' proposal [Bac 78] a new school of
thought is emerging in the field of programming language design.
His main objection against the conventional programming
languages is that they are growing ever more enormous, but not
stronger because of their inherent defects at the most basic
level. They are founded on word - at - atime programming
inherited from their ancestor Von Neumann computer and their
semantics is closely coupled to the state transition. They
have more <u>rigid</u> parts and less <u>variable</u> parts because of their
closed coupling to the state transition and dividing the
programming into a world of statements and world of expressions.
Whereas, the world of expressions is orderly and has useful
mathematical properties, the world of statements is chaotic.
Because of these aspects they are unable to effectively use
powerful combining forms to build new programs from the existing
ones, and they lack useful mathematical properties. His
proposal is to adopt a truely variable less functional program-
ming language which has less <u>rigid</u> parts and more <u>variable</u>

parts. Such functional programs are often nonrepetitive and
nonrecursive, are hierarchically constructed, do not name
their arguments and donot require complex procedure declarations.
Functional programming can easily use higher level programs
to build still higher level ones. Since programs, their
semantics, and their realizations are defined in the same
language, a simple algebra of programs can be used for program
transformations.

We believe that some of the aspects discussed above are
important for the next generation of programming languages which
will be required to deal with systems of still-yet-unimagined
complexity.

1.4 Overview of the thesis

Since the thesis extensively uses the presently available
Id constructs to describe proposed extensions, Chapter 2 briefly
describes Id and its constructs. Block expressions, conditional
expressions, loop expressions, procedures, monitors, and
programmer defined data types are discussed. To show the use
of some of these constructs, Id program to compute Fast Fourier
Transform of a signal sequence is described.

Chapter 3 deals with sequential looping constructs,
mixed looping constructs and generators. An alternate
translation of _for_ loops using _for_ _each_ loop and generator is

discussed. This view of _for_ loops makes the translation of mixed _for_ loop constructs easy. A simplified translation of _for_ _each_ - _while_ loop is also discussed, and, its usefulness in the controlled generation of the elements in a _for-while_ loop and in a pdt, is shown.

Chapter 4 describes stream structures which are useful in maintaining a variable and a large number of queues. Dynamic stream construct of Id is reviewed and some base language operators are extended to allow streams as creation time parameters for Id monitors. Usefulness of the stream structures in the resource management problems is shown through an example.

Chapter 5 discusses the programmer defined constructs, which enable a programmer to define his own constructs and aids in program abstraction. Syntax for its definition and its use, and, its implementation is described. To bring out some of the relevant points and limitations several examples are discussed.

In Chapter 6 we present our conclusions and observe that some of the concepts discussed in the thesis can also be incorporated in conventional languages to enhance their capabilities.

CHAPTER 2

Id: A BRIEF INTRODUCTION

This chapter is intended to make the reader familiar with
the high level dataflow language Id (Irvine dataflow) together
with the syntax and . the underlying semantics of its constructs
[AGP77, AGP78].

2.1 Id and the underlying model of execution[*]

Id is a block structured, expression oriented, single
assignment language whose syntax resembles Algol-type of block
structured language. Id provides facilities for resource
handling via dataflow monitors; incorporates data abstraction
mechanisms (i.e. programmer defined data types), and is
extensible.

Id like any other dataflow language is based on the
principle of dividing computation into smaller subcomputations
called activities which may be executed by independent
processing elements. Every Id program is compiled into a
corresponding program in the base language which is an ordered
graph consisting of operators interconnected by directed lines
that transport values in the form of tokens. A variable in

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[*]This section or rather this complete chapter relies heavily
on the description of Id given in [AGP78] .

an Id program does not represent the name of a memory cell, rather it is the name of a line in the base language graph along which the value travels. Id variables are not typed. The internal representation of values is self identifying and thus, type is associated with a value and not a variable. A given variable in Id or a line in program graph is either a simple variable or a stream variable [Wen 75]. A simple variable carries a single token to each instance of an operator's execution, while a stream variable carries a linearly ordered sequence of tokens to each instance of an operator's execution. Id variables are strongly typed as far as streams are concerned. Throughout the thesis simple variables will be denoted by lower case letters and stream variables by upper case letters. Base language programs corresponding to Id programs are executed on a dataflow machine using Unravelling Interpreter [AG77a]. The unravelling interpreter dynamically removes ordering between operations due only to time, while retaining orderings required by the need for partial results. This scheme of interpretation does an automatic unfolding of loops and permits simultaneous execution of distinct invocations of the same operation. This brings out far more asynchrony then what is normally possible in a dataflow language [Den 73, AG77a]. Underlying dataflow machine does not have memory in the convntional sense. The values are carried by tokens.

Memory is used only to store values that are too large to be moved efficiently; instead a pointer to stored value is carried by the token. Thus existence of memory is completely transparent to the Id programmer.

2.2 Id values and basic schemas

Id values are of nine types: integer, real, boolean, string, structure, procedure definition, monitor definition, monitor object, and errors. First four need no explanation. We will explain structures here, rest of them will be treated in later sections. A structure value is either the empty structure Λ or a set of < selector: value > ordered pairs. A selector is an integer, real, boolean, or string value; a value is any Id value. There are exactly two operators defined over structures -- SELECT and APPEND [AGP78]. The important thing to note is that an append operation always creates a logically new structure, and the original structure may enjoy a simultaneous existence. Multiple selectors are allowed.

We explain three basic schemas in Id: block expression conditionals, and loops.

2.2.1 Block expressions:

Any Id program can be written as a list of expressions. However, it is convenient to break a computation and identify certain partial results. An example of block expression is

$$x,y \leftarrow (x \leftarrow b * 2 + a;$$

$$y \leftarrow 2 * a$$

$$\underline{return} \ x + y,y) \qquad\qquad (2.1)$$

The <u>inputs</u> to the block expression are those variables
which are referenced but not assigned in the block and <u>outputs</u>
(ordered) are specified by <u>return</u> clause. The compilation of
expression is shown in Figure 2.1. An <u>assignment statement</u>
names the line in corresponding base language graph. Id limits
the scope of names to the block in which they are defined.
Thus x,y have different values inside and outside the block in
expression (2.1). A <u>constant</u> like 2 in Id does not represent
a value but function that produces that value as its output
regardless of the value of the input. Box C in Figure 2.1
represents such a function.

2.2.2 <u>Conditional expressions</u>:

A conditional expression in Id is of the form

$$(\underline{if} \ p(x) \ \underline{then} \ f(x) \ \underline{else} \ g(x)) \qquad\qquad (2.2)$$

Its base language translation is given in Figure 2.2. The
SWITCH operator passes the token coming on data line to the
T branch or the F branch depending on whether token on control
line carries the value <u>true</u> or <u>false</u>. If any of the branch
(T or F) is not connected and the control input dictates that
branch to be taken, then the data token is simply absorbed. The
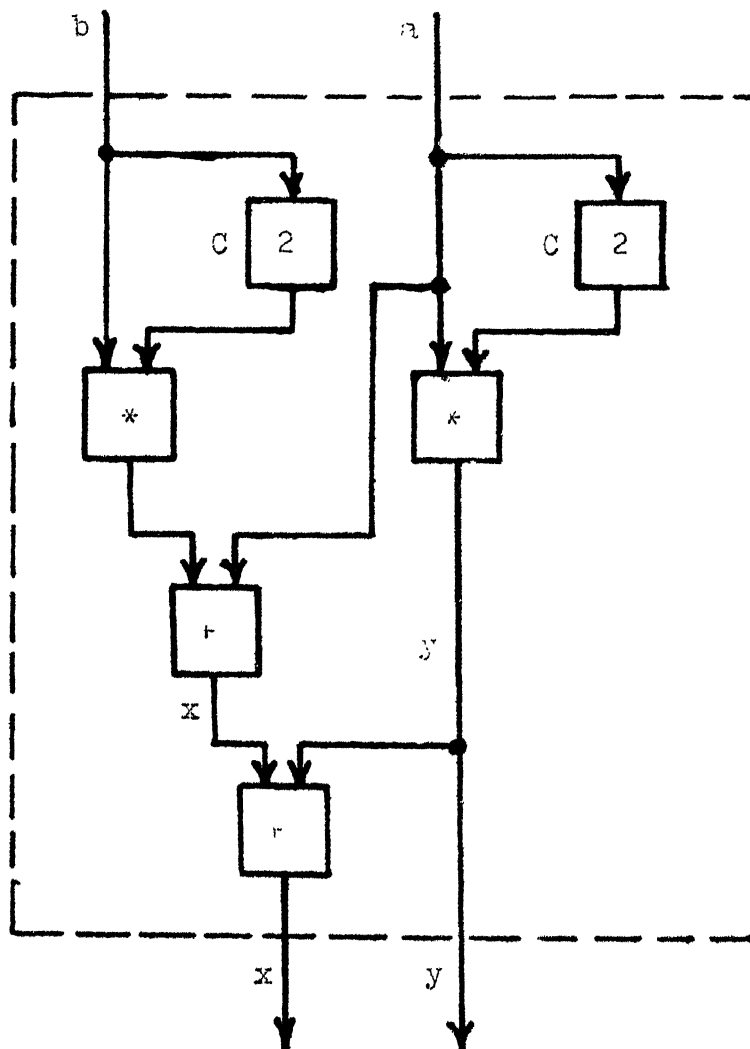
Figure 2.1   Compilation of the block expression (2.1).
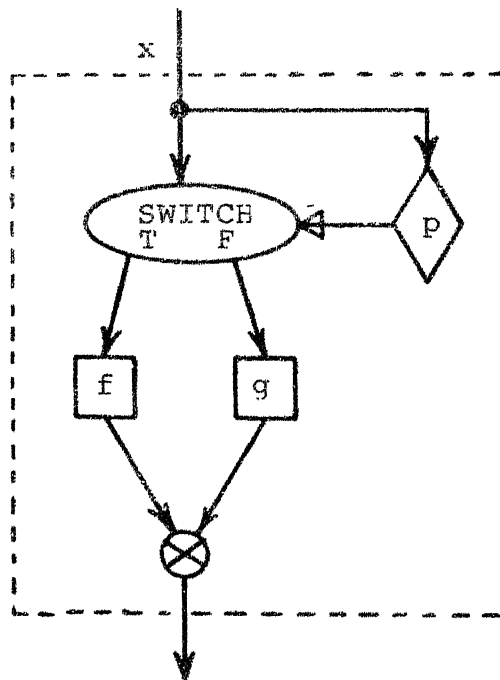
Figure 2.2   Compilation of the conditional
             expression (2.2).

Ⓧ operator merges the two branches of conditional expression.
A conditional expression needs all of its inputs for execution
regardless of the branch to be taken. In a conditional
expression the <u>then</u> clause and the <u>else</u> clause should contain
equal number of expressions. Conditionals can also be written
in the statement form. Thus expression (2.3) and expression
(2.4) are equivalent.

$$(\underline{if}\ p(x)\ \underline{then}\ y \leftarrow f(x);\ z \leftarrow 1\ \underline{else}\ y \leftarrow g(x);\ z \leftarrow 0) \quad (2.3)$$

$$y, z \leftarrow (\ \underline{if}\ p(x)\ \underline{then}\ f(x),\ 1\ \underline{else}\ g(x),\ 0\ ) \quad (2.4)$$

2.2.3 <u>Loop expressions</u>:

Basic loop construct in Id is a <u>while</u> loop (loops
involving streams are different). A <u>while</u> loop is given in
expression (2.5) and its compilation in Figure 2.3

$$(\underline{initial}\ i \leftarrow 1;\ sum \leftarrow 1$$
$$\underline{while}\ sum \leq s\ \underline{do}$$
$$\underline{new}\ i \leftarrow i + 1;$$
$$\underline{new}\ sum \leftarrow sum + i$$
$$\underline{return}\ sum, i) \quad (2.5)$$

Variables initialized in the <u>initial</u> part and all loop
constants such as s circulate in the loop domain. For the next
iteration of the loop their new values are defined by loop
body. A default for loop constants is that their new values
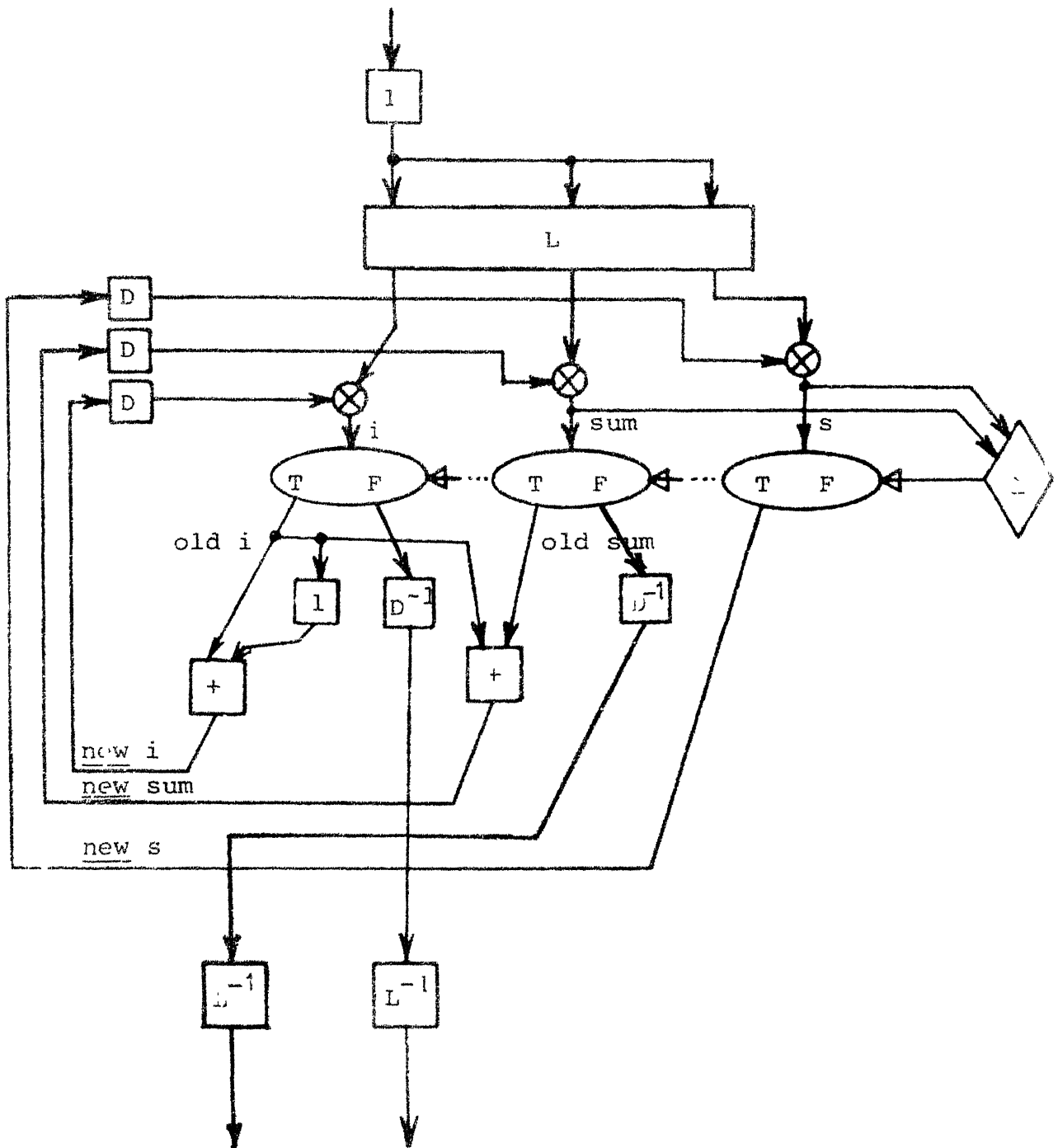
Figure 2.3   Compilation of the loop expression (2.1).

are same as old values. The operators L, L^{-1}, D, D^{-1} do not
affect the values of the tokens passing through them. They
are used by the unravelling interpreter to manipulate <u>activity</u>
<u>names</u> so that tokens belonging to different instantiations
of a loop do not get mixed up with the tokens belonging to
different iterations of a loop instantiation. <u>new</u> i is used
to la<u>be</u>l a line which is different from i and does not violate
the single assignment rule.

Id supports many kinds of looping constructs such as
<u>for</u> loops, <u>for-while</u> loops etc. However,they are compiled in
form of a basic <u>while</u> loop. Expression (2.6) gives a <u>for-while</u>
loop whose equivalent <u>while</u> loop is given in expression (2.7).

    (<u>initial</u> x ← f(x)

    <u>for</u> i <u>from</u> 1 <u>to</u> n <u>while</u> p(x) <u>do</u>

      y ← g(i);

      <u>new</u> x ← f(x)+y

    <u>return</u> x)   (2.6)

    (<u>initial</u> x ← f(x)

    <u>while</u> i ≤ n ⋏ p(x) <u>do</u>

      y ← g(i);

      <u>new</u> x ← f(x) + y;

      <u>new</u> i ← i+1

    <u>return</u> x)   (2.7)

A basic looping construct involving streams is given in
expression (2.8).

> (<u>initial</u>   s ← a
>
> <u>for</u> <u>each</u> x <u>in</u> X; y <u>in</u> Y <u>while</u> p(x,y) <u>do</u>
>
>   <u>new</u> s ← s+x+y;
>
>   z ← f(x,y);
>
>   <u>if</u> z≤ t <u>then</u> b ← <u>next</u> p
>
>   <u>else</u> b ← λ
>
> <u>return</u> s, <u>all</u> z, <u>all</u> b <u>but</u> λ)   (2.8)

There are many points brought out by this expression
which are relevant when dealing with streams. A <u>for</u> <u>each</u>
loop operates on all the elements of a stream. Expression
(2.8) shows a parallel looping construct in which for each
iteration of a loop an element from X and an element from Y
are taken. Loop terminates when predicate p is satisfied, or
either of the two streams runs out of tokens.   <u>all</u> z is a
stream producing construct and returns a stream containing
all the values of z. <u>but</u> λ performs what one intuitively
expects it to do: it filters out λ's from the stream <u>all</u> b.
<u>next</u> P construct gives next element from the stream P, when
asked, and thus avoids circulating the streamP. <u>next</u> only
has meaning when it is inside a conditional construct which is
embedded in a loop expression. Compilation of expression (2.8)

is too involved and is given in Sections 4.2.3.2 and 4.2.3.3
of [AGP78]. We will show a simpler implementation of the
loops involving next in Chapter 4.

2.3 Procedure definition and application

A procedure definition in Id is a constant value and
it may be created by writing:

$$p \leftarrow \text{procedure} \ (x) \ (\text{if} \ x > 1 \ \text{then} \ x - 1$$
$$\text{else} \ x + 1) \qquad (2.9)$$

x is a formal parameter, and the expression is the
procedure body. p is the name of the line along which the
token carrying the procedure value will travel. In Id two
operators are defined over procedure values:
APPLY and COMPOSE. Apply applies the procedure definition
to a list of actual arguments. We write an application as

res ← apply (p, arg)

where arg is actual argument. A syntactic shorthand is

res ← p (arg)

The primitive apply is implemented as two base
language operators: A and A^{-1} as shown in Figure 2.4. The
A actor accepts the procedure definition and creates an
instance of its execution. It then sends the actual
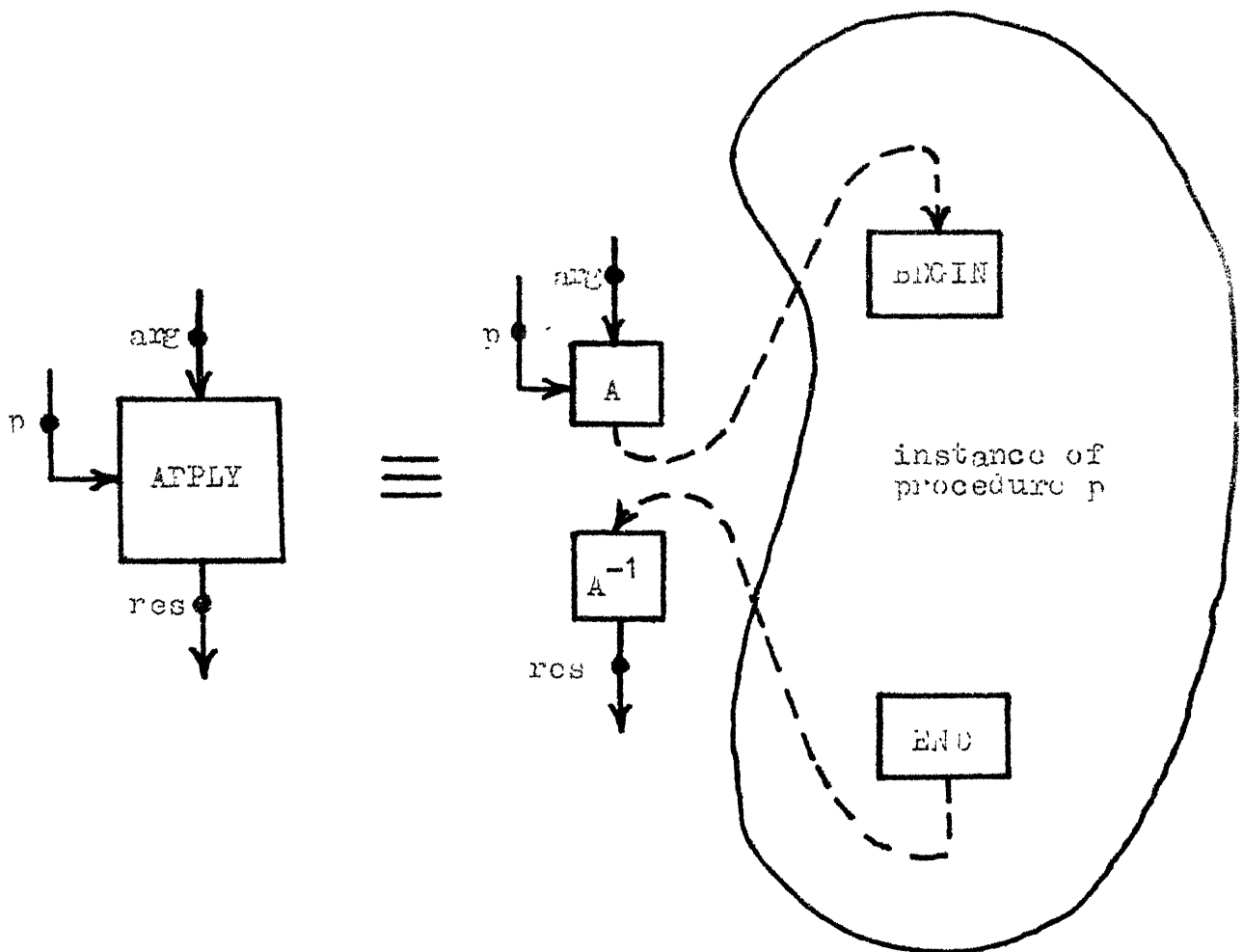
Figure 2.4 A procedure application.

arguments to this instance. The results of computation are returned to A^{-1} and the instance of the procedure is automatically destroyed. Distinct instances are created for the application of the same procedure at different places.

Compose operator takes the input procedure value and "freezes" one or more of the procedure's formal parameters to particular actual values. For example, in

$$a \leftarrow \underline{procedure} \ (b,C) \ (b * c + b/c);$$
$$d \leftarrow \underline{compose} < a, \ < 2 > > \qquad (2.10)$$

d behaves as if programmer had written

$$d \leftarrow procedure \ (c) \ (2 * c + 2/c)$$

It is possible to give a $\underline{name}$ to an Id procedure. This is useful in writing recursive procedures. Whenever a named procedure is applied its definition is also passed as an argument. Expression (2.11) gives a recursive procedure to calculate factorial function.

$$y \leftarrow \underline{procedure} \ f(n) \ (\underline{if} \ n = 0 \ \underline{then} \ 1 \ \underline{else} \ n * f(n-1))$$
$$(2.11)$$

compose and named procedures are useful in programmer defined data types. Procedure's arguments are not limited to simple variables, stream variables are also allowed.

2.4 Dataflow monitors[*]

The concept of a dataflow monitor [AGP77, AGP78] was introduced in order to allow nondeterministic behaviour generally encountered in resource management. Expression (2.12) assigns a dataflow monitor definition value to variable md.

$$md \leftarrow \underline{monitor} \ (s_o)$$

$$(\underline{entry} \ REQ \ \underline{do}$$

$$RES \ \leftarrow \ (\underline{initial} \ s \ \leftarrow \ s_o$$

$$\underline{for \ each} \ req \ \underline{in} \ REQ \ \underline{do}$$

$$\underline{new} \ s, \ ans \ \leftarrow \ f(s, \ req)$$

$$\underline{return} \ \underline{all} \ ans$$

$$\underline{exit} \ RES) \qquad\qquad (2.12)$$

Many instances of monitor objects may be created from this monitor definition. Creation of a monitor instance is done by

$$me \ \leftarrow \ \underline{create} \ (md,a) \qquad\qquad (2.13)$$

A programmer refers to the monitor object by writing me. a is the initial state passed at the creation time. An

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[*]In [AGP78] word manager is used in place of monitor.

instance of a monitor is not created and destroyed for only one invocation, but may be reused arbitrarily during its life span by sending to it arguments, which will be processed in a FIFO order. There exist only one instance of me and all the uses of me refers to that instance only.

A monitor instance is shown in Figure 2.5. The <u>entry</u> operator receives all requests and forms a stream by merging the requests nondeterministically. This stream is passed to the monitor's body. The <u>exit</u> operator converts the output stream to simple tokens and returns them to the place from where requests originated.

To use a monitor object we write

$$z \leftarrow \underline{use} \ (me, \ y) \tag{2.14}$$

The compilation of this statement is given in Figure 2.6. The U operator sends the argument (y) to the domain indicated by me. The result is returned to U^{-1} operator and assigned to variable z.

Since the internal state of a monitor acts as a memory, the processing of a particular request may depend on the history of the previous inputs sent to the monitor.

Id provides another nondeterministic operator: <u>merge</u>. It merges the streams specified in its argument list
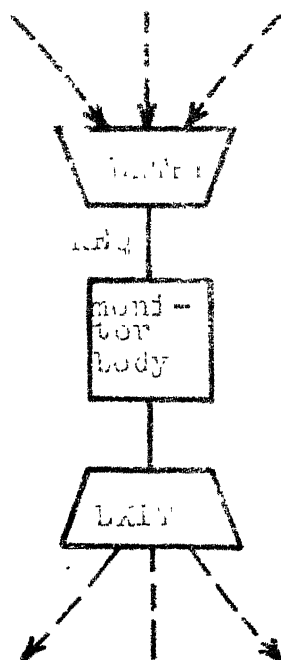
Figure 2.5 An instance of a monitor.
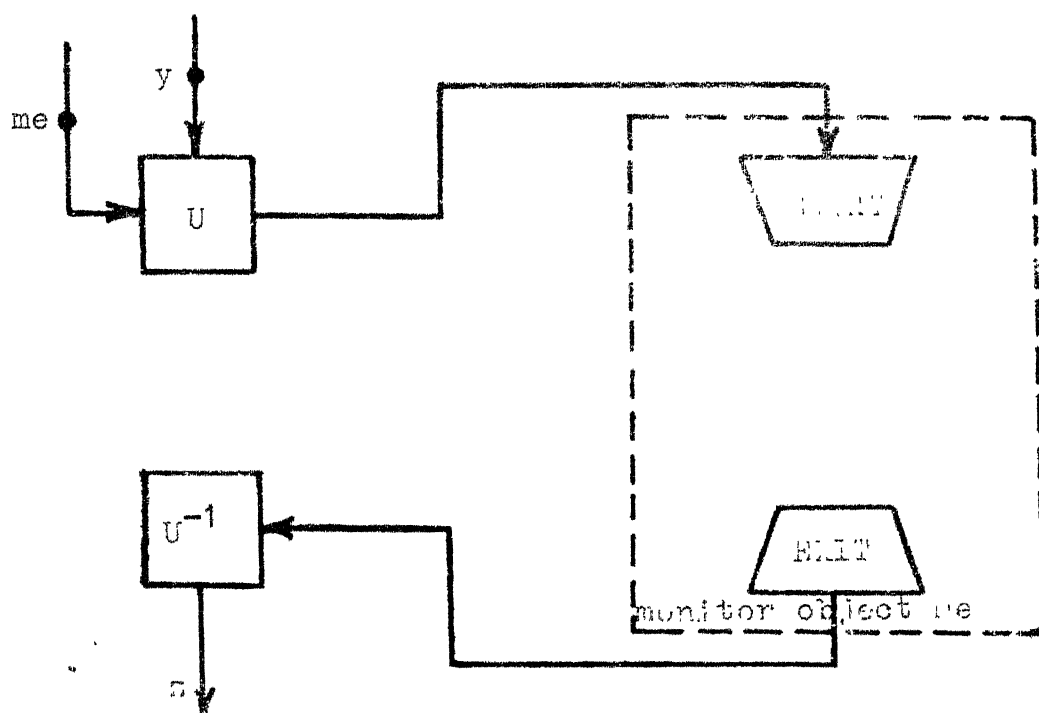
nondeterministically and creates a new stream. Expression (2.15) shows the use of merge.

$$C \leftarrow \underline{merge}\ (A,B) \qquad\qquad (2.15)$$

2.5 Programmer defined data types

In Id, a procedure definition value is treated exactly like any other value. This general view of a procedure allows Id to provide some very sophisticated higher-level concepts while requiring only minimally expended lower-level mechanisms. These higher-level concepts include programmer-defined data types (pdts) and operator extensionality so operators such as "+" may be interpreted at execution time in the context of the types of their arguments.

Expression (2.16) gives a pdt 'set' with four operations. Operation 'ε' decides set membership and returns a boolean value. '+' denotes set insertion and returns a new set value. New set value is created using the procedure set-gen. 'U' and 'Ω' denote set union and set intersection operations.

```
procedure set-gen (s,l)

(y ← procedure set (! function! f, ! arguments! u,v,
                     ! set array! s, !cardinality! l, set-gen)

    (if f= "ε" then (initial t ← false;
                     for i from 1 to l while t do
                     new t ← s [i] = v
                     return t)

     elseif f = "+" then (if |ε| (u,v) then u
                                       else set-gen(s+[l+1]v,
                                                    l+1))

     elseif f = "U" then (initial b ← v
                          for i from 1 to l do
                          new b ← b+ s [i]
                          return b)

     elseif f =" "then (initial b ← set-gen ( )
                        for i from 1 to l do
                        (if|ε|(v,s [i])then new b ← b+s[i])
                        return b)

     else error: (<'invalid set operation', f > ))

return (if s = ξ then compose (y, < ,,, Λ ,0, set-gen> )
                 else compose (y, < ,,, s, l, set-gen>-)))
```

$$(2.16)$$

Actual values of sets are created by calling the procedure set-gen. The procedure set-gen returns a procedure value 'set' with two frozen parameters s and l which characterize that set. Thus a pdt is always a procedure. To generate a new set a we write

$$a \leftarrow set\text{-}gen \; (s,l)$$

where structure s contains the elements of a and l is the cardinality of a. Similarly to create an empty set we write

$$a \leftarrow set\text{-}gen \; (\;\;)$$

An operation, such as set insertion (+), can be performed by writing

$$b \leftarrow | \; + | \; (a, \; 17) \qquad\qquad (2.17)$$

Expression (2.17) creates a new set b and it is translated as

$$b \leftarrow \underline{apply} \; (a, \; +, \; a,17) \qquad\qquad (2.18)$$

Expression 2.18 can also be written as

$$b \leftarrow a + 17$$

and in this case the meaning of operator + is determined at execution time.

If the operator + receives a procedure value on line a, it dynamically changes itself to an <u>apply</u> operator to evaluate the expression of the form (2.18).

2.6 An example

In the previous sections we have discussed the mechanisms provided by Id. To show the use of these mechanisms, we give an Id program to compute the Fast Fourier Transform of a discrete signal sequence. The signal sequence is represented as a stream.

```
procedure fast-fourier (X,j,n,w)
                        !X is the stream of the signal samples,
                         n is the number of the samples in
                         the original stream, w contains the
                         the values of W_n^k ,   where W_n =
                         e^{-j\frac{2\pi}{n}} , and j=2^i, where i denotes
                         the level at which we are working.
                         Initially j should be 1 .!
(if empty (rest (X)) then X
  ! stream is divided into two parts containing odd and even
    numbered samples.
else ( P,Q ← (initial flag ← true
              for each x in X do
                 (if flag then p ← x;q ← λ )
                          else p ←λ ; q ← x);
              new flag ← ⌐ flag
              return all p but λ, all q but λ );
     S ← fast-fourier (P, 2*j, n, w);
     T ← fast-fourier (Q, 2*j, n, w);
     U,V ← (initial i ← 0
             for each s in S; t in T do
               a ← w[n, i*j ]+t ;
               u ← s + a ;
               v ← s - a ;
             new i ← i + 1
             return all u, all v)
      return concatenate (U,V)))                    (2.19)
```

Keeping the asynchronous input and output behaviour
of the streams in mind, a rough analysis of the above program
will show that it takes $O(n+\log_2 n)$ time, whereas, a corres-
ponding program on a sequential machine will take $O(n \log_2 n)$
time [KAT78b]. However, the above program requires atleast
$O(n)$ processors to execute in the time complexity of
$O(n+\log_2 n)$. This proves the point that Id is able to exchange
processors with time. As a passing point we would like to
mention that most of the algorthims, such as merge-sort
[KAT78a] etc., show this tendency. However, certain conventional
algorithms which are efficient on sequential machines turn out
to be inefficient when translated in Id. Thus it is
reasonable to assume that to exploit asynchrony inherent in
the problem it is not sufficient to translate existing
algorithms into Id or any other dataflow language. Instead
new algorithms must be invented and analyzed to derive
benefits of asynchrony [Mal 78].

CHAPTER 3

SEQUENTIAL LOOPS, MIXED LOOPS, AND GENERATORS

In this chapter we discuss many aspects of looping constructs in Id and show that the idea of generators and iterators can be incorporated in Id very easily. As a complement to parallel loops we propose sequential looping construct, that is loops of nested nature, and generalize these constructs to include any combination of sequential and parallel loops i.e. mixed looping constructs. Sections 3.2 and 3.3 deal with sequential looping constructs and their efficiency considerations. Section 3.4 explains syntax and translation of mixed for each loop constructs. Section 3.5 shows how the idea of generators can easily be incorporated in Id. Section 3.6 presents an alternate translation of for loop in terms of for each loop using the concept of a special generator i to j. This view of for loops makes the translation of mixed for loop constructs easy. Section 3.7 discusses a simplified translation of for each - while loop. Section 3.8 extends the ideas developed in Section 3.7 to control the generation of elements in a for - while loop and in a pdt. Finally Section 3.9 shows how the ideas of sections 3.4, 3.6, 3.7 and 3.8 can be used to translate mixed looping constructs with while clause.

3.1 Background and motivation

As described in Chapter 2, Id [AGP 78] provides many kinds of looping constructs to operate on simple as well as stream variables. For the sake of comprehensiveness we list them below.

(a) while p(x) do where p(x) is some boolean expression
(b) for i from j to k by l do and
    for i from j to k by l while p(x) do
(c) for each x in X do
(d) for each x in X; y in Y do
(e) for each x in X; y in Y while p(x,y) do

Loop expressions like any other expressions in Id can be nested to any arbitrary depth. At present, loop expressions involving next in Id are different from (a) to (e). However, with a simpler implementation of next described in Chapter 4 (section 4.5), the present discussions will be valid to loop expressions involving next also.

Our motivation to go for sequential and mixed looping constructs is to make programmer's task easier. Consider an Id program to sum all the elements of a n x m matrix given in expression (3.1).

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```
(initial  sum ← 0

for i from 1 to n do

   new sum ← sum + (initial  sum ← 0

                    for j from  1 to m do

                       new sum ← sum + a[i,j]

                    return sum)

     return sum )                                    (3.1)
```

Id forces one to initialize the sum twice. One can imagine the programmer's burden when the levels of nesting goes beyond three or four. Syntactically it will be more convenient for a programmer to write

```
(initial  sum ← 0

for i from 1 to n,

    j from 1 to m do

   new sum ← sum + a[i,j ]

return sum)                                          (3.2)
```

However, translation of above construct is rather difficult in terms of existing compilation of for loops. The translation is considerably simplified if we view 1 to n as a generator generating successive values of the loop variable i. Another motivation to incorporate generators is to extend looping constructs to iterate over the elements of a pdt without giving undue emphasis on the order of enumeration.

Hiding the order of enumeration is a useful concept because in many data structures, such as sets, there is no implicit ordering (in mathematical sense) defined over their elements. CLU [LSAS77], ALPHARD [SWL77] and EUCLID [LHLMP77] already provide such an extended view of looping constructs to iterate over the elements of an abstract data type.

3.2 A sequential looping construct for ID

Since a semicolan is used to define a parallel looping construct (see (d) and (e)) let a comma separating two clauses of a loop (as in expression (3.2)) define their sequential or nested nature[*]. Hence the meaning of

for each i in I, j in J do

is that for each element of i take each element of J one by one and execute one iteration of the loop. Hence the loop body will be executed $|I| X |J|$ times as opposed to $\min\{|I|, |J|\}$ times (as in the case of a parallel loop). Implementation of a sequential loop is quite straightforward and is explained below in terms of an equivalent Id program not involving such a construct.

---

[*] The use of comma here is different from UCI dataflow Note 11 (revised).

$$(\underline{\text{initial}} \ x_- \leftarrow x_O$$
$$\underline{\text{for}} \ \underline{\text{each}} \ i \ \underline{\text{in}} \ I, \ j \ \underline{\text{in}} \ J \ \underline{\text{do}}$$
$$\underline{\text{new}} \ x \quad \leftarrow f(x,i,j)$$
$$\underline{\text{return}} \ x) \tag{3.3}$$

The loop in expression (3.3) can be implemented as

$$(\underline{\text{initial}} \ x \leftarrow x_O$$
$$\underline{\text{for}} \ \underline{\text{each}} \ i \ \underline{\text{in}} \ I \ \underline{\text{do}}$$
$$\underline{\text{new}} \ x \leftarrow (\underline{\text{initial}} \ -x \leftarrow x$$
$$\underline{\text{for}} \ \underline{\text{each}} \ j \ \underline{\text{in}} \ J \ \underline{\text{do}}$$
$$\underline{\text{new}} \ x \leftarrow f(x,i,j)$$
$$\underline{\text{return}} \ x)$$
$$\underline{\text{return}} \ x) \tag{3.4}$$

There are some subtle issues involved in the correct translation of expressions contained in the $\underline{\text{return}}$ clause of expression (3.4). An equally efficient but somewhat more straightforward translation of (3.3) is given in (3.5). The expression in (3.5) does not affect the body of the loop. Only the input streams I and J are suitably enlarged to I' and J', each of which has a length $|I| \times |J|$. We prefer to translate expression (3.3) into expression (3.5) rather than expression (3.4) as the scheme of expression (3.5) is useful in translating mixed looping constructs.

$$(I', J' \leftarrow (\underline{for} \; \underline{each} \; i \; \underline{in} \; I \; \underline{do}$$
$$I',J' \leftarrow (\underline{for} \; \underline{each} \; j \; \underline{in} \; J \; \underline{do}$$
$$\underline{return} \; \underline{all} \; i, \; \underline{all} \; j)$$
$$\underline{return} \; \underline{all} \; I', \; \underline{all} \; J')$$
$$\underline{return} \; (\underline{initial} \; . \; x \leftarrow x_0$$
$$\underline{for} \; \underline{each} \; i \; \underline{in} \; I'; \; j \; \underline{in} \; J' \; \underline{do}$$
$$\underline{new} \; x \leftarrow f(x,i,j)$$
$$\underline{return} \; x)) \tag{3.5}$$

The construct $\underline{return} \; \underline{all} \; X$ returns a stream as opposed to a stream of streams.

3.3 Efficiency of sequential loop expression

Expression (3.2) for summing all the elements of a matrix can be translated into expression (3.6) in a mechanical way.

$$(\underline{initial} \; . \; sum \leftarrow 0$$
$$\underline{for} \; i \; \underline{from} \; 1 \; \underline{to} \; n \; \underline{do}$$
$$\underline{new} \; sum \leftarrow (\underline{initial} \; sum \leftarrow sum$$
$$\underline{for} \; j \; \underline{from} \; 1 \; \underline{to} \; m \; \underline{do}$$
$$\underline{new} \; sum \leftarrow sum + a[i,j]$$
$$\underline{return} \; sum)$$
$$\underline{return} \; sum) \tag{3.6}$$

Note that expression (3.6) is considerably less asynchronous than expression (3.1) due to the fact that all

the additions in (3.6) are done sequentially. In expression
(3.1) summation of elements within a row is still sequential
but it proceeds simultaneously for all the rows. While
expression (3.1) will take $O(n)$ time, expression (3.6) will
take $O(n^2)$ time. It is possible to mechanically transform
expression (3.6) into expression (3.1) but this is quite a
difficult task because it involves meanings of many non-control
operators in Id. It is reasonable to assume that in general
when nested loop expressions are expressed as sequential loops
a loss of asynchrony is involved. Thus the ease in writing
may come at the expense of efficiency.

3.4 Mixed looping constructs

In order to generalize parallel and sequential looping
constructs we consider the following two proposals.

(i) for each (i in I; j in J), (k in K; l in L) do

(ii) for each (i in I, j in J); (k in K, l in L) do

The loop in (i) should go through $\min\{|I|, |J|\} \times$
$\min\{|K|, |L|\}$ iterations while the loop in (ii) should go
through $\min\{|I| \times |J|, |K| \times |L|\}$ iterations. Semantics of
expressions of type (i) are given in expression (3.7) while
the meaning of (ii) is given in expression (3.8).

$$(I', J', K', L' \leftarrow (\underline{for}\ \underline{each}\ i\ \underline{in}\ I;\ j\ \underline{in}\ \textbf{J}\ \underline{do}$$

$$I',\ J',\ K',\ L' \leftarrow (\underline{for}\ \underline{each}\ k\ \underline{in}\ K;$$

$$l\ \underline{in}\ L\ \underline{do}$$

$$\underline{return}\ \underline{all}\ i,\ \underline{all}\ j,$$

$$\underline{all}\ k,\ \underline{all}\ l)$$

$$\underline{return}\ \underline{all}\ I',\ \underline{all}\ J',\ \underline{all}\ K',\ \underline{all}\ L')$$

$$\underline{return}\ (\underline{for}\ \underline{each}\ i\ \underline{in}\ I';\ j\ \underline{in}\ J';\ k\ \underline{in}\ K';\ l\ \underline{in}\ L'\ \underline{do}$$

$$.$$

$$.$$

$$.))\hspace{3cm}(3.7)$$

$$(I',\ J' \leftarrow (\underline{for}\ \underline{each}\ i\ \underline{in}\ I\ \underline{do}$$

$$I',\ J' \leftarrow (\underline{for}\ \underline{each}\ j\ \underline{in}\ J\ \underline{do}$$

$$\underline{return}\ \underline{all}\ i,\ all\ j)$$

$$\underline{return}\ \underline{all}\ I',\ \underline{all}\ J');$$

$$K',\ L' \leftarrow (\underline{for}\ \underline{each}\ k\ \underline{in}\ K\ do$$

$$K',L' \leftarrow (\underline{for}\ \underline{each}\ l\ in\ L\ do$$

$$\underline{return}\ \underline{all}\ k,\ all\ l)$$

$$\underline{return}\ \underline{all}\ K',\ \underline{all}\ L')$$

$$\underline{return}\ (\underline{for}\ \underline{each}\ i\ \underline{in}\ I',\ j\ \underline{in}\ J';\ k\ \underline{in}\ K';\ l\ \underline{in}\ L'\ \underline{do}$$

$$.$$

$$.$$

$$.))\hspace{3cm}(3.8)$$

It is clear from these examples that we can build quite complex <u>for</u> <u>each</u> constructs by combining i <u>in</u> I type of clauses

either in a sequential way or in a parallel way. Implement-
ation of such complex for each constructs requires no
additional base language operators.

3.5 Stream producers as generators

As pointed out in Section 3.1 a useful control
abstraction present in CLU [LSAS77] and ALPHARD [SWL77] is
that of a generator. It offers a way of hiding the order of
enumeration of the elements of an abstract data type when
such an order is unnecessary. For example a generator may
enumerate all the elements of a set or all the elements of an
array for addition without making the order of enumeration
explicit. A related problem is to enumerate the elements of
a programmer defined data type when its internal structure
is not known.

Something equivalent of generators can be defined very
easily in Id using streams. In general any expression producing
a stream can be treated as a generator. The elements of a
stream X can be enumerated using a for each x in X do construct.
Since the order of enumeration depends upon the construction of
X, the problem of hiding the order of enumeration becomes the
problem of hiding the generation of X. Since X will be gener-
ated by an expression and the internal functioning of no
expression in Id is visible from outside, the problem of hiding
or abstracting is essentially solved. We elaborate this point

further by giving examples. Suppose we want to sum the elements
of a set s where s is a programmer defined datatype in Id. We
could accomplish this in the following way in Id.

Define a function "enumerate" on sets and include it in
the procedure set-gen (see Section 2.5). The procedure set
(produced by procedure set-gen) when supplied with "enumerate"
as a parameter would produce a stream containing all the elements
of the set. The order of enumeration will depend upon the
definition of the function "enumerate" inside the procedure set.
The programmer using sets would just write

for each e in |enumerate| (s) do

Since the definition of a procedure application in Id
allows streams to be input as well as output there is no problem
in generating a stream from a pdt. It is also clear that such
enumeration procedures can be defined for any pdt. However, we
can avoid generating a stream from the pdt, if we desire so, by
breaking the operation into two parts. Define a function on a
pdt that gives all its elements stored in a linear structure
with selectors 1 to n. A procedure that converts such an array
into a stream is trivial to write. This method, however, fails
with those pdts that have countably infinite number of
elements. We will discuss this problem further in
section 3.7.

3.6 An alternate translation of for loops using a special generator

Values of i generated by the for loop

for i from j to k do

can also be modelled as the following stream

$$I \leftarrow (\underline{initial}\ i \leftarrow j$$
$$\underline{while}\ i \leq k\ \underline{do}$$
$$\underline{new}\ i \leftarrow i+1$$
$$\underline{return}\ \underline{all}\ i) \qquad\qquad (3.9)$$

The stream I can now be used in place of from j to k as

for each i in I do

Eventhough the loop for i from j to k do results in a different base language translation, the answers produced by two loop expressions will be identical except in one detail. Suppose the last value of i is to be returned from the loop. The from j to k loop will produce the value k+1 while for each i in I loop will give an error. Several solutions to this minor problem are possible and we will not discuss them here any further. We would like to point out that both for loop and for each loop in this case are equally efficient.

One might be wondering about our motivation to translate for i from 1 to n type of loops into slightly more

complicated <u>for</u> <u>each</u> i <u>in</u> I type of loop. As we hope to show
in the next few sections this approach helps considerably in
translating sequential looping constructs of the type given in
expression (3.2). Without this technique of converting <u>for</u>
loops into a <u>for</u> <u>each</u> loop implementation of the following
construct is extremely difficult.

$$\text{\underline{for}} \ (i \ \underline{from} \ 1 \ \underline{to} \ n, \quad j \ \underline{from} \ 1 \ \underline{to} \ m);$$
$$(k \ \underline{from} \ 1 \ \underline{to} \ q, \quad l \ \underline{from} \ 1 \ \underline{to} \ r) \ \underline{do} \qquad (3.10)$$

Let us introduce a new stream expression of the following
type in Id

$$I \leftarrow j \ \underline{to} \ k.$$

The meaning of this expression is given in (3.9). The trans-
lation of the mixed looping construct of (3.10) now can be
explained as follows:

$$(I \leftarrow 1 \ \underline{to} \ n; \ J \leftarrow 1 \ \underline{to} \ m; \ K \leftarrow 1 \ \underline{to} \ q; \ L \leftarrow 1 \ \underline{to} \ r$$
$$\underline{return} \ (\underline{for} \ \underline{each} \ (i \ \underline{in} \ I, \ j \ \underline{in} \ J); \ (k \ \underline{in} \ K, \ l \ \underline{in} \ L)\underline{do}$$
$$\ldots)) \quad (3.11)$$

Similarly we can translate any type of mixed looping
construct.

3.7 <u>For</u> <u>each</u> - <u>while</u> type of loop revisited

Consider the following type of loop expression whose
translation is discussed in [AGP78] in some detail.

(<u>initial</u> : $x \leftarrow x_0$

  <u>for</u> <u>each</u> b <u>in</u> B <u>while</u> p (b,x) <u>do</u>

    <u>new</u> $x \leftarrow f(b,x)$

  <u>return</u> x)   (3.12)

The main feature of the translation is that a signal
stream S controls the release of tokens from stream B into the
loop. Or equivalently a token of stream B enters the loop
on demand only. How we will describe a slight modification
of the scheme given in [AGP78].

The translation of expression (3.12) can be simplified
to the one given in Figure 3.1 provided the loop of expression
(3.12) satisfies the following property P.

$$p(b_i, x_i) = \underline{false} \twoheadrightarrow b_{i+1} = \underline{est}$$

where b_i is the ith token of stream B and x_i is the input value
for the ith iteration of the loop. The property P guarantees
that stream B runs out of tokens exactly when the loop predicate
p turns <u>false</u>.

In general property P does not hold for a loop. However
we can always convert any <u>for</u> <u>each</u> - <u>while</u> loop to one for
which property P does hold good. The technique is explained
below by using the same example (i.e. expression (3.12)).
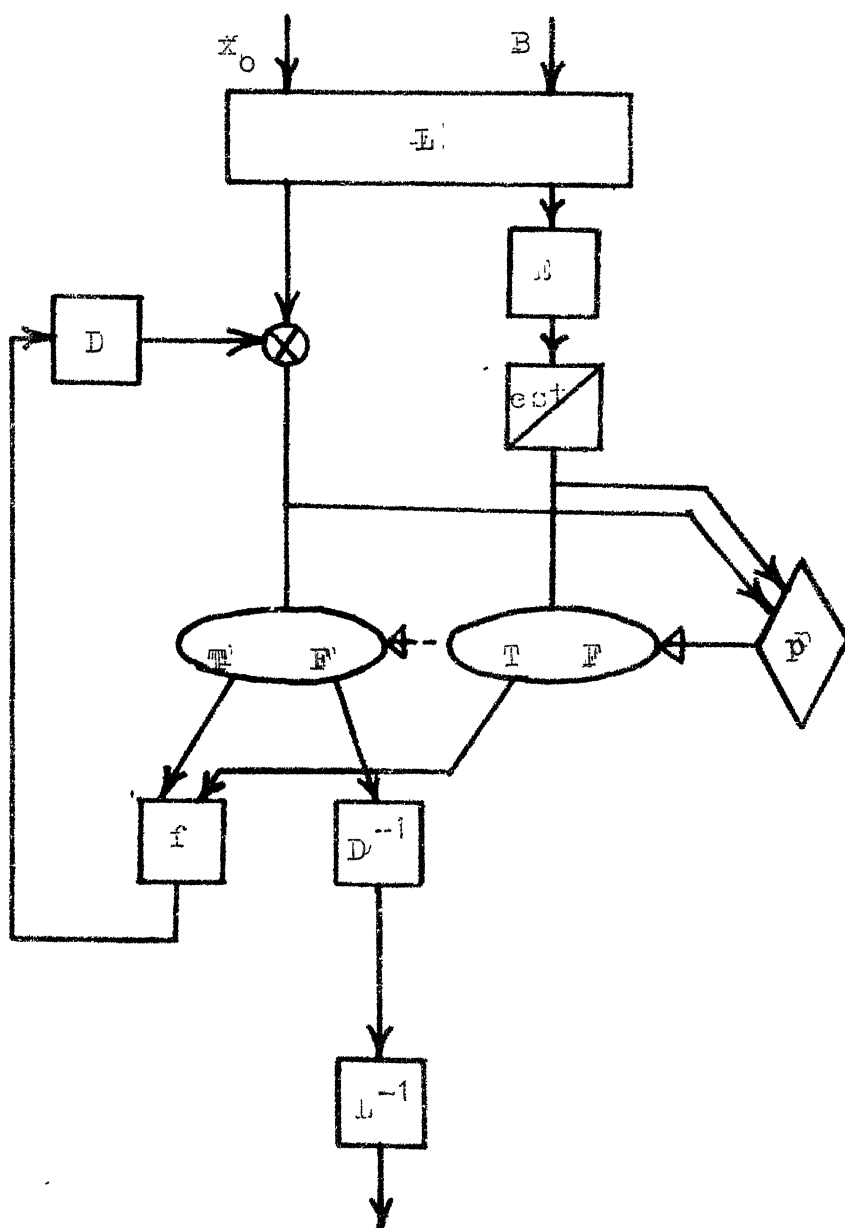
Figure 3.1 Simplified for each-while loop.

However, now we assume that property P is not satisfied by the loop in (3.12).

$$(x, S' \leftarrow (\underline{initial}\ x \leftarrow x_0$$
$$\underline{for}\ \underline{each}\ b\ \underline{in}\ B'\ \underline{while}\ p(b,x) \wedge b \neq \varepsilon\ \underline{do}$$
$$\underline{new}\ x \leftarrow f(b,x)$$
$$\underline{return}\ x,\ \underline{all}\ \underline{true});$$
$$S \leftarrow \underline{cons}\ (\underline{true}, S');$$
$$B' \leftarrow \underline{exif}\ (B,S,\ \varepsilon)$$
$$\underline{return}\ x) \tag{3.13}$$

It is clear that stream B' alongwith predicate $p(b,x)$ $b \neq \varepsilon$ satisfies property P provided no ε tokens are present in B. This is the same condition as in [AGP78b]. The translation of expression (3.13) differs from the translation of expression (3.12) according to the rules given in [AGP78] only to the extent that $\underline{exif}$ and $\underline{cons}$ will be outside the loop domain.

3.8 Controlled generation in a $\underline{for}$ - $\underline{while}$ loop and in a pdt

We consider the translation of the following looping construct

$$\underline{for}\ i\ \underline{from}\ 1\ \underline{to}\ n\ \underline{while}\ p(x)\ \underline{do} \tag{3.14}$$

An equivalent form involving generators will be

$$\underline{for}\ \underline{each}\ i\ \underline{in}\ I\ \underline{while}\ p(x)\ do \tag{3.15}$$

where I is the stream 1 $\underline{to}$ n.

The loop in (3.14) generates a value of i only when p(x) for the previous value of i is <u>true</u>. Hence if n > 10 and p(x) turns <u>false</u> at the 10th iteration, the values 11,12, ..., n for i are never generated. On the other hand, loop in (3.15) will always get in stream I the whole sequence 1,2,..., n eventhough it will simply absorb value 11,12,.... If n happens to be a infinitely large number, the program in (3.15) will not terminate while in case of (3.14) it will. This descripancy can be resolved by producing the tokens of stream I on demand. The technique described in Section 3.7 for generating a signal stream can be used to control the production of tokens in stream I. The details are given in expression (3.16).

$$
\begin{aligned}
&(\dots, \text{S'} \leftarrow(\underline{\text{initial}} \; . \\
&\qquad\qquad\qquad . \\
&\qquad\qquad\qquad . \\
&\qquad \underline{\text{for}} \; \underline{\text{each}} \; i \; \underline{\text{in}} \; I \; \underline{\text{while}} \; p(i,x) \wedge i \neq \varepsilon \; \underline{\text{do}} \\
&\qquad . \\
&\qquad . \\
&\qquad . \\
&\qquad \underline{\text{return}} \; \dots, \; \underline{\text{all}} \; \underline{\text{true}}); \\
&\text{S} \leftarrow \underline{\text{cons}} \; (\underline{\text{true}}, \; \text{S'}); \\
&\text{I} \leftarrow (\underline{\text{initial}} \; i \leftarrow 1 \\
&\qquad \underline{\text{for}} \; \underline{\text{each}} \; s \; \underline{\text{in}} \; S \; \underline{\text{do}} \\
&\qquad\quad \underline{\text{if}} \; i \leq n \; \underline{\text{then}} \; \underline{\text{new}} \; i \leftarrow i+1; \quad i' \leftarrow i \\
&\qquad\qquad\qquad\quad \underline{\text{else}} \; \underline{\text{new}} \; i \leftarrow \varepsilon; \; i' \leftarrow \varepsilon \\
&\qquad \underline{\text{return}} \; \underline{\text{all}} \; i') \\
&\underline{\text{return}} \; \dots)
\end{aligned}
$$

(3.16)

The signal stream S must be used in generating stream
I as opposed to just controlling its size after the whole stream
I has been generated. For example if we write

$$I' \leftarrow (\underline{\text{initial}}\ i \leftarrow 1$$
$$\underline{\text{while}}\ i \leq n\ \underline{\text{do}}$$
$$\underline{\text{new}}\ i \leftarrow i+1$$
$$\underline{\text{return}}\ \underline{\text{all}}\ i);$$
$$I \leftarrow \underline{\text{exif}}\ (I',\ S,\ \varepsilon) \qquad\qquad (3.17)$$

then the whole purpose of stream S is defeated.

Finally we discuss how this idea of controlled generation
may be used in conjuction with a pdt. A pdt is essentially a
procedure and hence can accept a stream as an input parameter
and produce a stream as an output parameter. A programmer can
generate an appropriate signal stream S and use it in enumer-
ating the elements of a pdt. The technique for generating
and using signal stream is same as the one described in the
above examples. We think that all such programming should be
explicit so that no new semantic extensions are required.

We explain by giving a very simple example where the
elements of a set are to be enumerated until an element
satisfies some predicate p. Let s be a pdt representing
a set.

```
(! the calling procedure !
    •
    •
    •
.., S'←(initial
        •
        •
        •
        for each x in X while ⌐ p(x,Y) ∧x ≠ ε   do
            •
            •
            •
        return ..., all true);
    S ←cons (true, S' );
    X ← |enumerate| (s,S);
    •
    •
    •                        )                    (3.18)
```

Internal structure of s would look something like the
following

<u>procedure</u> set (f,u,v, set-gen, a,l,S)

!all formal parameters have the usual meaning

  S - a stream parameter has been added!

(<u>if</u> f = ...

      •

      •

      •

<u>elseif</u> f = "enumerate" <u>then</u> RESULT ←(<u>initial</u> i ←1

                                  <u>for each</u> signal

                                      <u>in</u> S <u>do</u>

                             <u>if</u> i ≤1 <u>then</u>

                                    x ← a [i]

                                <u>else</u> x ← ε

                       <u>return all</u> x)

$$(3.19)$$

3.9 <u>Mixed looping construct with a while clause</u>

The loop of the type <u>for each</u> i <u>in</u> I, j <u>in</u> J <u>while</u> p(i,j,x) <u>do</u> can be compiled in two steps. First transform the sequential loop into a parallel loop according to the method discussed in section 3.2. Hence we will get

<u>for each</u> i <u>in</u> I'; j <u>in</u> J' <u>while</u> p(i,j,x) <u>do</u>

which can be translated either according to the rules given in [AGP78] or the rules given in section 3.7. Hence all looping

constructs involving streams can be translated.

The ideas developed so far can be suitably extended to specify efficient translation of sequential and mixed loops of the following type:

<u>for</u> i <u>from</u> 1 <u>to</u> n, j <u>from</u> 1 <u>to</u> m <u>while</u> p(i,j,x) <u>do</u>   (3.20)

<u>for</u> (i <u>from</u> 1 <u>to</u> n, j <u>from</u> 1 <u>to</u> m);

   (k <u>from</u> 1 <u>to</u> q, l <u>from</u> 1 <u>to</u> r) <u>while</u> p(i,j,x) <u>do</u> (3.21)

An extension of the idea present in the translation of expression (3.14) to expression (3.16) leads to the following translation of expression (3.20)

$$(\ldots,, \; S' \leftarrow (\underline{initial} \; .$$

$$.$$
$$.$$

$$\underline{for} \; \underline{each} \; i \; \underline{in} \; I; \; j \; \underline{in} \; J \; \underline{while} \; p(i,j,x) \wedge$$
$$i \neq \epsilon \wedge j \neq \epsilon \quad \underline{do}$$

$$.$$
$$.$$
$$.$$

$$\underline{return} \; \ldots, \; \underline{all} \; \underline{true});$$

$$S \leftarrow \underline{cons} \; (\underline{true}, \; S');$$

$$I, J \leftarrow (\underline{initial} \; i \leftarrow 1; \; j \leftarrow 1$$

$$\underline{for} \; \underline{each} \; s \; \underline{in} \; S \; \underline{do}$$

$$(\underline{if}(i \leq n) \wedge (j < m) \underline{then} \; \underline{new} \; j \leftarrow j+1; \; i' \leftarrow i; \; j' \leftarrow j$$

$$\underline{elseif}(i < n) \wedge (j=m) \; \underline{then} \; \underline{new} \; i \leftarrow i+1; \underline{new} \; j \leftarrow 1;$$
$$i' \leftarrow i; \; j' \leftarrow j$$

$$\underline{else} \; i' \leftarrow \epsilon; \; j' \leftarrow \epsilon)$$

$$\underline{return} \; \underline{all} \; i', \; \underline{all} \; j')) \quad\quad\quad (3.22)$$

It should be noted that in expression (3.22), the first loop satisfies property P and the moment i' and j' get the value both the loops terminate.

A translation of mixed looping construct of (3.21) is given in expression (3.23) in terms of the rules used in expressions (3.8) and (3.22).

$.(\ldots, S' \leftarrow (\underline{initial}$.
$\qquad \qquad \qquad \bullet$
$\qquad \qquad \qquad \bullet$

$\qquad \underline{for} \ \underline{each} \ i \ \underline{in} \ I; \ j \ \underline{in} \ J; \ k \ \underline{in} \ K; \ l \ \underline{in} \ L$
$\qquad \qquad \underline{while} \ p(i,j,k,l,x) \wedge i \neq \epsilon \wedge j \neq \epsilon \wedge k \neq \epsilon \wedge l \neq \epsilon \ \underline{do}$
$\qquad \qquad \qquad \bullet$
$\qquad \qquad \qquad \bullet$
$\qquad \qquad \qquad \bullet$

$\qquad \underline{return} \ \ldots, \ \underline{all} \ \underline{true});$
$S \leftarrow \underline{cons} \ (\underline{true}, \ S');$
$I,J \ \leftarrow (\underline{initial} \ i \leftarrow 1; \ j \leftarrow 1$
$\qquad \underline{for} \ \underline{each} \ s \ \underline{in} \ S \ \underline{do}$
$\qquad \qquad (\underline{if} \ (i \leq n) \wedge (j < m) \ \underline{then} \ \underline{new} \ j \leftarrow j+1; \ i' \leftarrow i; \ j' \leftarrow j$
$\qquad \qquad \underline{elseif} \ (i < n) \wedge (j = m) \ \underline{then} \ \underline{new} \ i \leftarrow i+1; \ \underline{new} \ j \leftarrow 1;$
$\qquad \qquad \qquad \qquad \qquad \qquad i' \leftarrow i; \quad j' \leftarrow j$
$\qquad \qquad \underline{else} \ i' \leftarrow \epsilon; \ j' \leftarrow \epsilon)$
$\qquad \underline{return} \ \underline{all} \ i', \ \underline{all} \ j' \ );$
$K,L \ \leftarrow (\underline{initial} \ k \leftarrow 1; \ l \leftarrow 1$
$\qquad \underline{for} \ \underline{each} \ s \ \underline{in} \ S \ \underline{do}$
$\qquad \qquad (\underline{if} \ (k \leq q) \wedge (l < r) \ \underline{then} \ \underline{new} \ l \leftarrow l+1; \ k' \leftarrow k; \ l' \leftarrow l$
$\qquad \qquad \underline{elseif} \ (k < q) \wedge (l = r) \ \underline{then} \ \underline{new} \ k \leftarrow k+1; \ \underline{new} \ l \leftarrow 1;$
$\qquad \qquad \qquad \qquad \qquad \qquad k' \leftarrow k; \ l' \leftarrow l$
$\qquad \qquad \underline{else} \ k' \leftarrow \epsilon; \ l' \leftarrow \epsilon)$
$\qquad \underline{return} \ \underline{all} \ k', \ \underline{all} \ l'))$
$\qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad (3.23)$

3.10 Summary

In this chapter we have modified the implementation of for loops from that given in [AGP78] and as explained in Chapter 2. This has been done to extend looping construct to include sequential and mixed type of loops. An explanation in Id is offered for the implementation of for each - while loop. This new explanation with its virtue of being in Id is applicable to many programming situations where a controlled generation of elements is required. At this stage it seems that the only fundamental looping scheme is

for each x in X; y in Y while p(x,y) do

Both the while loops and for each loops without while clauses can be explained as special cases of the above loop. All the other sequential and mixed looping constructs have already been defined in terms of this fundamental parallel looping construct with a while clause.

Generators as used in the literature so far can be expressed in Id without any extensions. Since pdts are basically procedures, controlled generation of elements even in case of a pdt is no problem.

CHAPTER 4

STREAM STRUCTURES

In this chapter we discuss the concept of arrays of streams, which will be called stream structures, and show their usefulness in modelling the problems related to the area of resource management. After motivating to stream structures in Section 4.1, we review the dynamic stream construct of Id in Section 4.2 and show its use by an example in Section 4.3. In Section 4.4 it is shown that stream structures can be incorporated in Id without extending the base language. We extend the semantics of some base language operators in Section 4.5 to permit streams as creation time parameters for Id monitors. Finally in Section 4.6 a complete example showing the use of stream structures is discussed.

4.1 Motivations

A problem in the area of resource management is how to maintain a queue of requests for a resource or a group of resources. In many instances a distinction among requests has to be made depending on their certain attributes, such as priority etc., to implement various scheduling policies [Bri 73, Sha 74]. In such cases many queues have to be maintained to distinguish between different requests.

Streams in Id offers a natural way to model the first-in-first-out queue[*]. In order to maintain several queues a stream variable can be defined for each queue. In a monitor definition in Id an entry port corresponding to each queue can also be defined. However, if the number of queues is large and dynamic addition and deletion of queues is required, then certainly, we cannot use the above idea. What we need is a model in which we can address a queue in the form A [i] , where A is the group of queues and i is the distinguishing attribute of the queue we are referring to.

The dynamic stream construct in Id [AGP77] offers a way of maintaining a variable number of queues, however, it imposes a restriction that all streams comprising a dynamic stream have to be dealt in an uniform manner. Our main motivation to go for stream structures is to provide a mechanism to model a large and a variable number of queues in which individual queue can be addressed and operations can be performed on its elements.

4.2 Dynamic streams[@]

As described above a dynamic stream is a set of streams whose elements are to be treated in an uniform manner. No

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[*]In this chapter streams and queues will be used synonymously.
[@]This description of dynamic streams is taken from personal notes of Dr. Arvind and Wil Plouffe.

explicit mechanism for selecting a particular stream is
provided. Id provides exactly one construct for the creation
and manipulation of dynamic streams. The construct is
explained in expression (4.1).

(dswitch I ← S via L
do
  J ← (. . .)
    .
    .
    .
  dmerge J via M)   (4.1)

The operator dswitch creates a distinct logical stream
I_j for each distinct value j in the stream L. Stream I_j will
contain only those tokens of S for which the corresponding
token of L has the value j. As an example

dswitch I ← [a,b,c,d,e,f,g] via [1,3,2,3,3,1,1]

would create the dynamic stream I with logical streams

$I_1 \equiv$ [a,f,g] , $I_2 \equiv$ [c], $I_3 \equiv$ [b,d,e]

The operator dmerge is the inverse of dswitch and
creates a single stream using the dynamic stream J according
to the specification stream M by removing one token from the

logical stream J_j when the next token from M carries the
value j. As an example, if the value of the stream M is
[2,3,3,1,3,1,1], and the stream components of dynamic
stream J are

$$J_1 \equiv [a,b,c \ ] \ , \ J_2 \equiv [d], \ J_3 \equiv [e,f,g \ ]$$

then dmerge will produce stream[d,e,f,a,g,b,c] .

The operators dswitch and dmerge are deterministic in
nature. The code enclosed between dswitch-dmerge pair is
logically created and independently acted upon by each stream
of a dynamic stream. Inside a dswitch-dmerge pair a
programmer treats dynamic stream like an ordinary stream except
that he cannot use ordinary streams in conjunction with
dynamic streams. Below we discuss the U-interpreter semantics
of the operators dswitch and dmerge.

4.2.1 dswitch:

As mentioned above dswitch creates a distinct logical
stream (I_j) for each distinct value (j) in the selection
stream (L). It does so by changing the context part of the
activity name. We give the U-interpreter semantics of
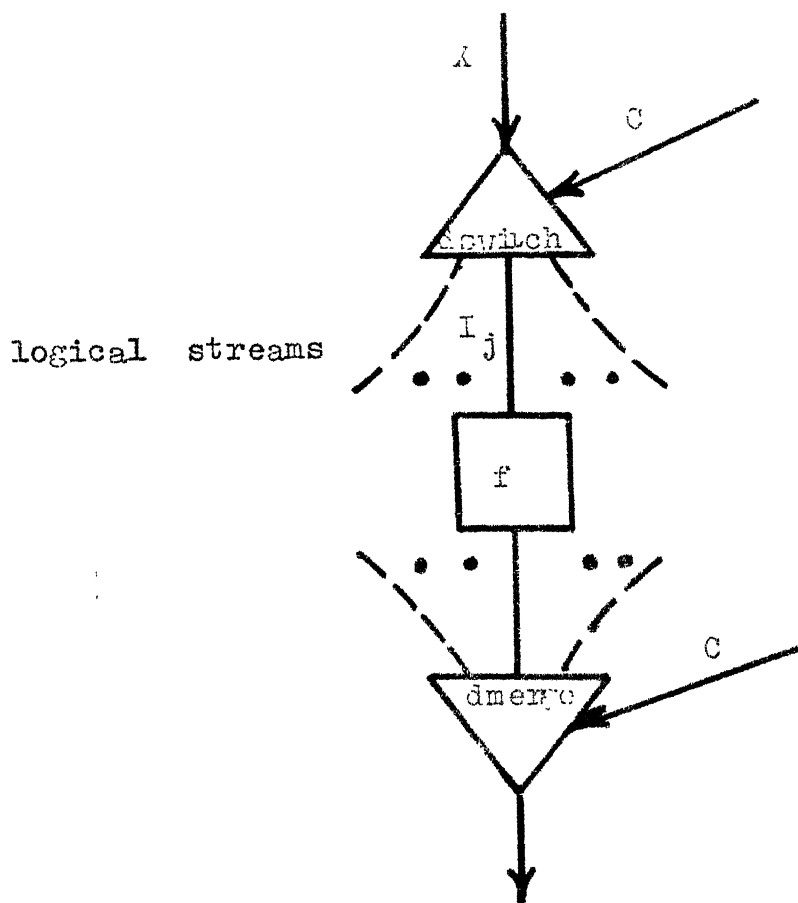dswitch used in the dynamic stream construct of Figure 4.1.

Figure 4.1 A dynamic stream construct.

u.p.s.i - - input: port1 (selection stream) $= \{<C_k, k> | 1 \leq k \leq n_c\}$

port2 (data stream) $= \{<X_k, k> | 1 \leq k \leq n_x\}$

output: (dynamic stream) $=$

$$\bigcup_{1 \leq k \leq n_c} (C_k \neq est \rightarrow (k \leq n_x \rightarrow \{<< X_k, count(C_k, k)>,$$

$$< (u.C_k).p.t.i >>\} ; \xi));$$

$$\bigcup_{j \in DL} \{<< est, count(j, n_c)>,$$

$$< (u.j).p.t.i >>\})$$

where $DL \triangleq \{j | j \triangleq C_k \text{ for some } k < n_c\}$

count $(j,k) \triangleq | \{i | C_i = j \text{ and } i \leq k\}|$

Thus to create logical streams context part of the activity name is changed from u to $u.C_k$. Since a logical stream is created for each distinct value of C_k, the logical streams are uniquely defined by the context part of the activity name. A logical stream is treated as an ordinary stream, and, thus it cannot have "holes" in it. For this reason dswitch maintains the number of elements passed to each logical stream by the function count. As soon as an est on selection stream is encountered, est tokens are produced for each logical stream. DL maintains all the distinct C_k values for this purpose.

4.2.2 dmerge:

As mentioned before

dmerge J via M

creates a single stream using the dynamic stream J according to specification stream M. This is done by taking an element

from the logical stream I_j when the next element from the stream M carries the value j.

We give the U-interpreter semantics of <u>dmerge</u> used in the dynamic stream construct of Figure 4.1. The description of <u>dmerge</u> is complicated by the fact that all streams of the dynamic stream have separate activity names and hence cannot be sent to the same operator. Thus <u>dmerge</u> has to be broken into two primitive operators: a <u>merge</u>$_c$ and a <u>merge</u>$_a$. The schematic representation of operators <u>merge</u>$_c$ and <u>merge</u>$_a$ is given in Figure 4.2.

a. <u>merge</u>$_c$: This operator operates on the control stream and for each token received by it, a token has to be produced by the dynamic stream construct of Figure 4.1. <u>merge</u>$_c$ essentially produces a stream of tokens for each of the <u>merge</u>$_a$ operators. The kth token received by the <u>merge</u>$_c$ operator carrying value c is forwarded to the <u>merge</u>$_a$ operator operating on the logical stream I_c to produce the kth token in the output stream.

$$u.p.s.i \; - - \; input:(control\ stream) = \{<C_k,k>|\ 1 \le k \le n_c\}$$

$$output = \underset{1 \le k \le n_c}{U} (k \ne n_c \rightarrow \{< k, count(C_k,k)>,$$

$$<(u.C_k).p.merge_a.i >\} \; ;$$

$$\{< \underline{est},\ k > <u.p.t.i >\} \;)$$
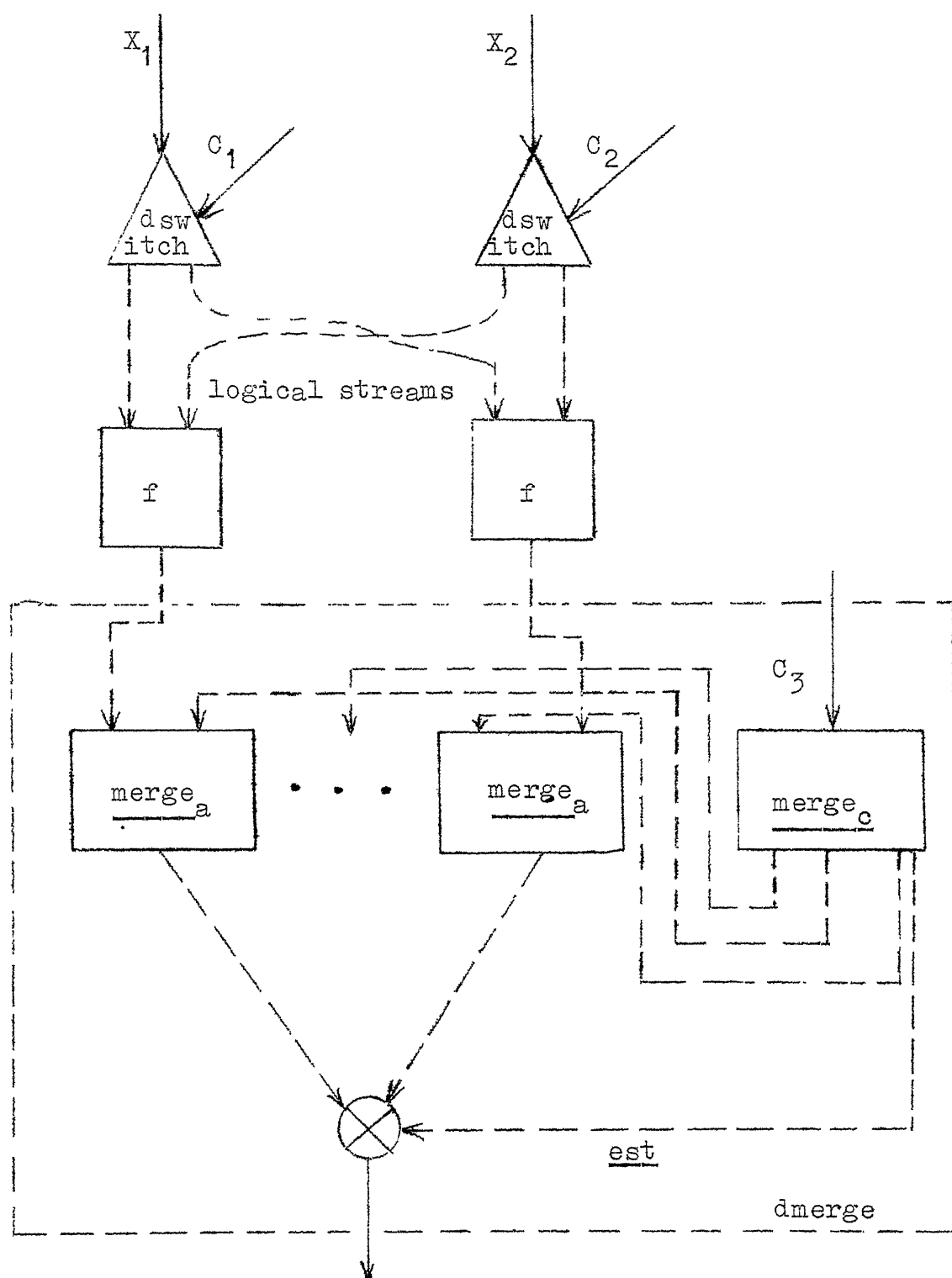
Figure 4.2 Schematic representation of $\underline{merge}_a$ and $\underline{merge}_c$.

Since $\underline{merge}_a$ operator is identified by the context $(u.C_k)$ of the logical stream on which it is operating, the context part of the activity name of the control tokens sent to $\underline{merge}_a$ operators is also changed to $u.C_k$. The $\underline{merge}_c$ operator has strong similarities with the $\underline{dswitch}$ operator, however, $\underline{merge}_c$ produces only one final $\underline{est}$ token as opposed to an $\underline{est}$ for each $\underline{merge}_a$.

b. $\underline{merge}_a$:   A $\underline{merge}_a$ operator is needed for each logical stream I_j of the dynamic stream I. A token produced by the $\underline{dmerge}$ comes from one of the $\underline{merge}_a$ operators. The $\underline{merge}_a$ operator which produces the kth token of the output stream is picked on the basis of the kth token received by the $\underline{merge}_c$ operator.

$$(u.j).p. \ merge_a.i \ -- \ input: \ port1(control \ stream)$$
$$= \{ <C_k,k> | \ 1 \le k \le p_c \}$$
$$port2(data \ stream)$$
$$= \{ <X_k,k > | 1 \le k \le p_x \}$$
$$output: \ (stream) = \underset{1 \le k \le p_c}{U} \ (k < p_x \{ <X_k,C_k>,$$
$$< u.p.t.i > \};$$
$$k = p_x \rightarrow \emptyset; \ \xi)$$

It should be noted that the dynamic stream construct of Figure 4.1 produces valid base language program. However,

the base language schema of Figure 4.2 will be self cleaning
only under certain conditions and those conditions, in general,
cannot be checked without executing the program. For self
cleaning streams C_1, C_2, C_3 must have the same number of each
integer present in them.

4.3 A disk scheduler monitor

We illustrate the use of dynamic streams by writing a
disk scheduler. To minimize disk-head-seek-time we implement
a scan policy in which disk head moves in one direction and
processes all the requests that fall ahead of it. If no
request lie ahead then the direction of scan is changed and
the same rule is followed again. If the disk head is busy and
a new request for cylinder c arrives, the counter count
associated with the cylinder c is incremented. Similar to
Hoare's monitor[Hoa74] we maintain a queue of requests for
every cylinder with the help of a dynamic stream DREQ. The
scheduler produces a stream giving the cylinder number of the
next request to be processed. This stream is then used to
form a dynamic stream of triggers: DTRIG, which in turn is used
to send signals to queues DREQ.

Once a request is allowed to proceed, it calls on another
monitor 'disk control' to actually seek the desired cylinder
and transfer data. This monitor may contain some of the actual

hardware of disk controller. A reply from disk control monitor signifies that the request has been processed. The disk scheduler monitor produces a result stream RESULT which is used to signal the scheduler that the current request has been processed. A schematic of disk scheduler is given in Figure 4.3 and Id implementation is given in Figure 4.4. We will not discuss the 'disk control' monitor.

4.4 Stream structures

As pointed out earlier, dynamic stream construct provides no way of selecting a particular logical stream. Consider a slight modification of the problem of disk scheduling discussed in Section 4.3. Suppose the disk scheduler should access two different physical disks depending on which group does the cylinder number belongs to. Solution of the problem using the dynamic stream would require the use of a case statement operating on all logical streams thus no longer maintaining problem structure in the solution. This solution is also likely to be inefficient in some cases. We will discuss these points further in Section 4.6.

In fact the dynamic stream construct in Id solves two problems associated with the resource management.

1. The dswitch operator is used to form large and variable number of queues. In doing so initial ordering of requests is maintained only within a particular queue.
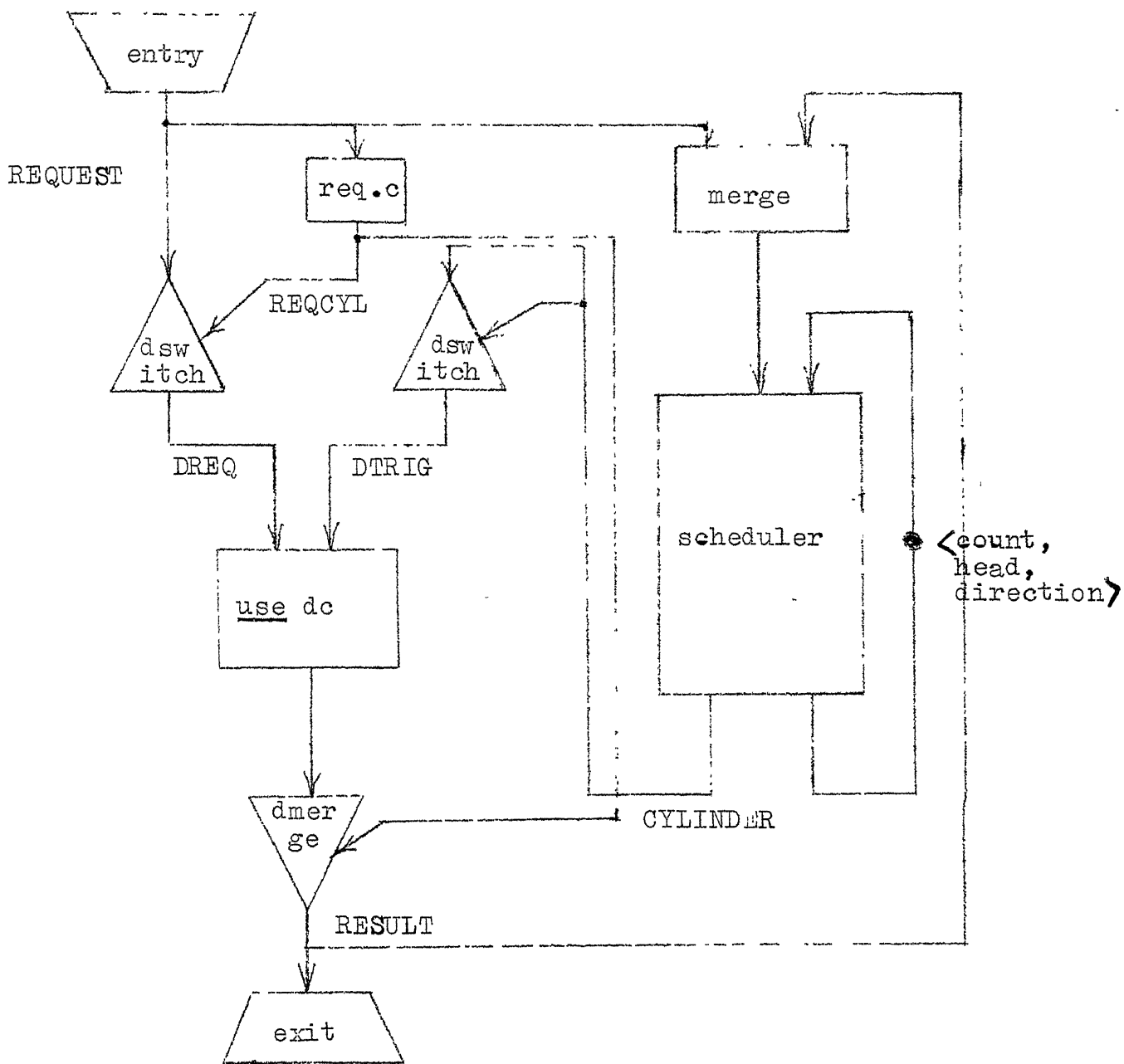
Figure 4.3   Schematic of disk scheduler monitor
of Figure (4.4).

```
monitor disk scheduler (dc)
! dc is the disk control monitor for the disk this scheduler
  is supposed to schedule!
(entry REQUEST do
        REQCYL ← (for each req. in REQUEST do
                    return all req.c);
        ! req.c gives the cylinder number!
        RESULT ← (dswitch DREQ ← REQUEST via REQCYL;
                        DTRIG ← CYLINDER via CYLINDER
                do
                        DRESULT ←(for each dreq in DREQ;
                                        t in DTRIG do
                                    dres ← use(dc,dreq)when t
                                return all dres)
                dmerge DRESULT via REQCYL);
        X ←merge (REQUEST, RESULT);
        ! This is scheduler code!
        CYLINDER ← (initial busy ← false; direction ←"up";
                        head ← ∅
                    for each x in X do
                      if x.type = "request"
                      then (if busy
                            then new count [x.c]← count [x.c]+1;
                                 cylinder ← λ
                            else new direction ←(if x.c > head
                                        .then "up"
                                        else "down" );
                                new head  ←c;
                                new busy  ←true;
                                cylinder  ←c)
                        else ! it is a done signal!
                        new count, new head, new direction,cylinder
                            ←findnext (count,head,cylinder);
                        new busy ←(if cylinder= λ then false
                                        else true))
                    return all cylinder but  λ)
  exit RESULT)

        Figure 4.4  Code for disk scheduler monitor.
```

2. The dmerge operator is used to restore the initial ordering by choosing the appropriate control stream (see the use of stream REQCYL in Figure 4.4).

Another solution to maintain a variable number of queues in which individual queue can be addressed is to introduce array of streams - which will be called as Stream Structure.

A stream structure is a stream in which each element has an associated qualifier which will be called "selector". The selector can be part of the activity name or part of the data itself. For further discussion we will assume it to be the part of data. Thus no new Id constructs or base language operators are required to deal with stream structures. An element of the stream structure is of the form:

<<< "data": x, "selector": int >, k > , < activity name >>

where int is a selector value. We will assume all selector values to be integers. A stream structure can also be regarded as an ordinary stream of structure values. Hence, all operators and constructs defined on simple streams are valid on stream structures also. In addition we define two Id procedures which are useful when dealing with stream structures.

a. select (A,i): A is a stream structure and i is a selector value. The result of procedure invocation is a stream containing those elements of A whose associated selector value equals i. Expression (4.2) gives details of the procedure.

procedure select (A,i)

(for each a in A do

res ←(if a ["selector"] = i then a ["data"]

else λ)

return all res but λ)   (4.2)

b. append (A,B,i):   A is a stream structure, B is a simple
stream, and i is a selector value. Result of procedure
invocation is a stream structure containing those elements of
A whose selector value is not equal to i and all elements
of B with their selector value made⁻ equal to i. Expression
(4.3) gives details of the procedure.

procedure append (A,B,i)

(RES1 ←(for each a in A do

res1 ←(if a ["selector"]= i then λ

else a)

return all res1 but λ);

RES2 ←(for each b in B do

res2 ← < "data": b, "selector":i >

return all res2)

return merge (RES1, RES2))   (4.3)

merge in the return clause of the procedure append is
used to cater for infinite streams. It can be replaced by
concatenate operator, if only finite streams are being considered

The use of <u>merge</u> makes the procedure append nondeterministic in behaviour. However, if we allow only <u>for</u> <u>each</u> loop and the procedure select to operate on stream structures, then either all the elements can be dealt in an uniform manner or a particular stream can be selected. Since <u>merge</u> does not change ordering of elements in component streams, the selected stream is always deterministic. Thus under these limitations the ultimate result will always be deterministic.

4.5 <u>Extension of Id monitors to include streams as creation time parameters</u>

The problem of maintaining queues is solved using stream structures. However once selection of a particular stream of a stream structure is done, the position of the elements of the selected stream within the original stream is lost. However, for correct functioning of Id monitors, it is required that a strict correspondence between the elements of input and output streams be maintained[*]. Hence, for stream structures to be useful in resource management problems, we need a way to restore the original order. We extend the monitors to include streams as creation time parameters and then we will

---

[*]Note if this is not the case, that is, the answer corresponding to the ith token of the input stream is in the jth position ($j \neq i$) of the output stream then the sender of the ith token will get the wrong answer (i.e., the ith token from the output stream).

use the extended monitor and dynamic streams to alter the ordering of elements in a stream structure.

We will allow the streams to be parameters in the construct create (see Section 5.2 of [AGP78]). For each stream parameter in create we provide separate port in operators C_2 and MBEGIN. A schematic of such extension is shown in Figure 4.5. Below we give the activity name manipulation by the operators C_1, C_2 and MBEGIN.

i. $\underline{C_1}$: This operator needs no change to accomodate streams as creation time parameters.

$$u.c.s_1.i \; - - \; input = c_m$$
$$output: port1 = <(u'.c_m.mbegin.1),$$
$$<u.c.s_2.i,1 >>$$
$$port2 = (u'.c_m.entry.1)$$

ii. $\underline{C_2}$: A separate port is created for each stream parameter.

$$u.c.s_2.i \; - - \; input: port1 = (u'.c_m.mbegin.1)$$
$$port2 = x$$
$$port3(stream) = \{<y,k> | \; 1 \leq k \leq n_y\}$$
$$output: port1 = <x, <u'.c_m.mbegin.1,1 >>$$
$$port2(stream) = \{< <y,k>$$
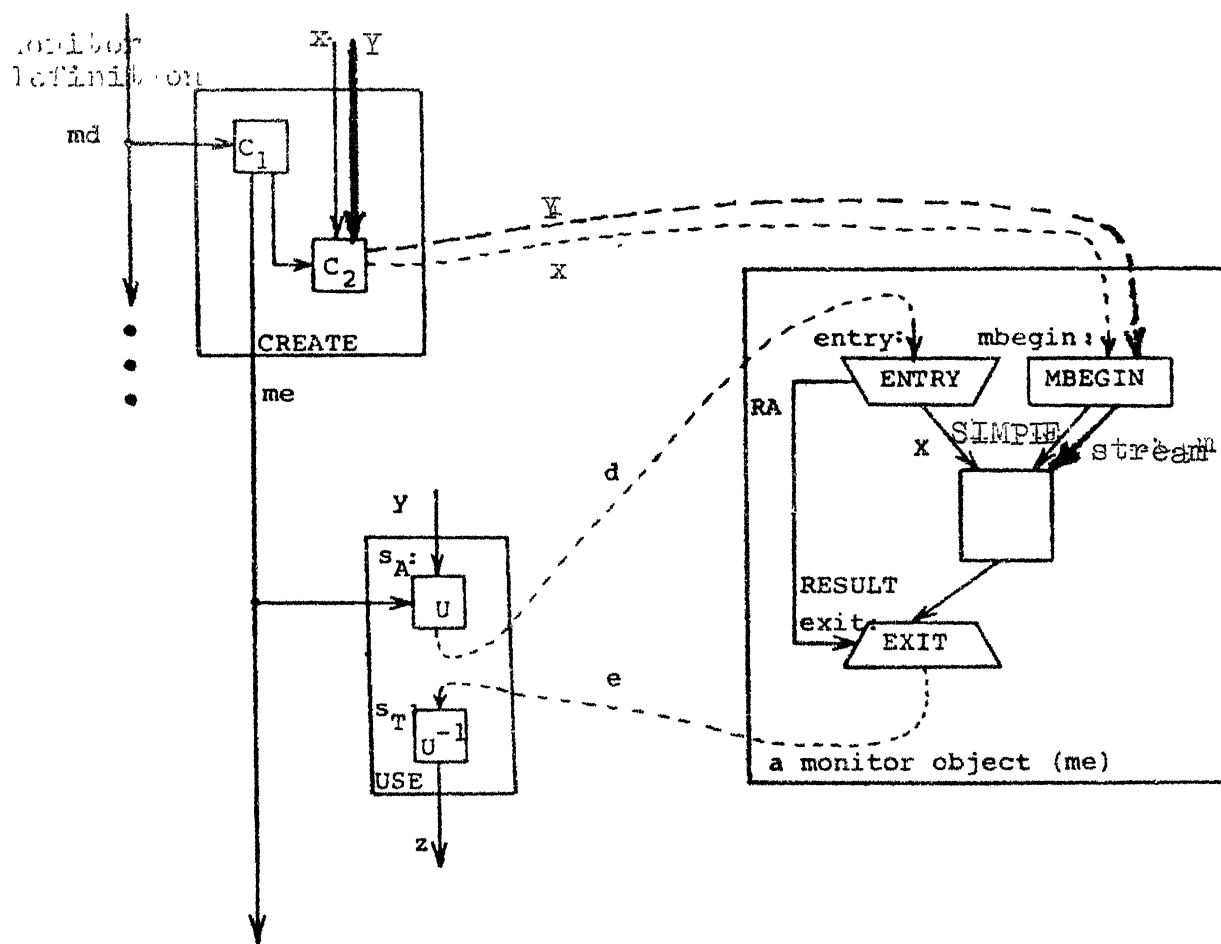$$<u'.c_m.mbegin.1,2 >>$$
$$| \; 1 \leq k \leq n_y\}$$

Figure 4.5 Schematic of extended monitor.

Thus the operator C_2 will remain in existence until it either receives est tokens on all streams or the monitor object is destroyed.

iii. MBEGIN:

$u'.c_m.$mbegin.1 -- input: port1(simple)=x

port2(stream)=$\{< y,k>|1 \leq k \leq n_y\}$

output: port1(simple)=x

port2(stream)= $\{< y,k >| 1 \leq k \leq n_y\}$

A monitor to alter the ordering of elements of a stream structure is given in expression (4.4).

monitor nexts (STREAM-ST)

(entry SELECTOR do

      RESULT $\leftarrow$ (dswitch DSEL $\leftarrow$ SELECTOR via SELECTOR;

                 DSTREAM-ST $\leftarrow$ STREAM-ST via

                      (for each s in

                          STREAM-ST do

                       return all s ["selector"])

          do

              RES$\leftarrow$ (for each ds in DSTREAM-ST;

                   dsel in DSEL do

             return ds when dsel)

      dmerge RES via SELECTOR)

  exit RESULT)   (4.4)

Use of an instantiation of such a monitor by
use (dnexts,c), where dnexts is a monitor object created from
monitor definition nexts, will give the next element in
the logical stream DSTREAM-ST$_c$. This is in fact, the next
element whose selector value is c in the stream supplied to
dnexts at creation time.

The effect of monitor nexts can also be achieved by
providing an entry port for stream STREAM-ST without extending
the monitors to include streams as creation time parameters.
Such a version of monitor nexts is given in expression (4.5)

```
monitor nexts ( )
(entry selector: SELECTOR; data: STREAM-ST do
        RESULT1 ← (dswitch DSEL← SELECTOR via SELECTOR;
                        DSTREAM-ST ←STREAM-ST via
                                (for each s in
                                        STREAM-ST do
                                   return all s[ "selector"])
        do
                RES← (for each ds in DSTREAM-ST
                            dsel in DSEL do
                           return all ds when dsel)
            dmerge RES via SELECTOR);
        ! we also need to acknowledge the processes sending
            elements of STREAM-ST at entry port "data"!
        RESULT2 ← (for each s in STREAM-ST do
                     return all 'acknowledged')
   exit selector: RESULT1; data: RESULT2)                (4.5)
```

The stream STREAM-ST is sent to an instance of nexts element by element as explained in program segment of expression (4.6).

```
dnexts ← create (nexts, )
(initial flag ← anything
   for each s in STREAM-ST do
     ack ← use (dnexts.data,s) when flag;
     new flag ←ack
   return ... )                                    (4.6)
```

Due to unfolding of loops in Id second iteration of loop in expression (4.6) may produce s before first iteration does so. Since the entry operator is nondeterministic, it will alter the ordering of elements in STREAM-ST. To avoid this we used a flag in expression (4.6). Flag will get a new value for the next iteration only when the previous iteration has completed the use of the monitor, thus forcing serial use of monitor instance dnexts. We want to emphasize the fact that any time a monitor is to be used sequentially it should be explicitly programmed by the programmer. Actually we are tempted to introduce a new U operator in the base language that will automatically ensure sequentiality in the use of a monitor. This new operator will receive an acknowledge signal from the entry of the monitor as soon as a token is

received. The advantage is, of course, one does not have to program explicit acknowledge signals, generating which can be quite clumsy in some cases.

Though monitor nexts in expression (4.5) is equivalent to monitor nexts in expression (4.4) as far as overall behaviour is concerned, monitor in expression (4.4) reflects the nature of the problem more clearly than the monitor in expression (4.5). Also limiting creation time parameters of a monitor to be simple variables is really not necessary.

Inside monitor nexts we use the dynamic streams to maintain queues and alter ordering. Such a use of dynamic streams offers two advantages:

    i. Dynamic streams can be made accessible only to monitor nexts thus avoiding the problem of unintentional mixing of dynamic streams with simple streams by users. This also gives a kind of desirable modularity to the program.

    ii. Semantics of monitor nexts is easier to understand than the semantics of a general dynamic stream construct. This is due to the fact that net effect of monitor nexts is only to alter the ordering unlike dynamic streams which perform two functions at a time.

As a passing point we would like to mention that the concept of monitor nexts can be applied to model next construct on streams. Expression (4.7) gives a monitor whose behaviour is equivalent to construct next.

```
monitor  next (X)
(entry REQ do
        Y ← exif (X,REQ, ε );
        RES ← (for each req in REQ; y in Y do
                  return all y)
exit RES )                                    (4.7)
```

As an example consider an Id program which uses the next operator.

```
Z ← (for each b in B do
      z ←(if b then next X
                else next Y)
      return all z)                           (4.8)
```

The above program can be written using monitor next as:

```
xnext ← create (next,X);
ynext ← create (next,Y);
Z ← (initial xsig← anything; ysig ←anything
    for each b in B do
      if b then z ←use (xnext, xsig);
                new xsig ← z;new ysig ← anything
            else z ← use (ynext, ysig);
                new xsig ← anything; new ysig ← z
    return all  z)                            (4.9)
```

4.6 An example

Consider a multiprogrammed, multiprocessor environment.
Suppose each processor is capable of performing several
different tasks, and the set of tasks performed by any processor
is exclusive of the sets of tasks performed by all the other
processors. There are several requests for each type of task.
We want to write an interface monitor which will schedule the
tasks on the processors. We will assume that there are only
two processors and different task types are numbered from
1 to 2n with 1 to n running on processor 1 and n to 2n
running on processor 2. Real world examples of such a system
would be a system like CRAY 1 [Rus78] having separate processors
for scalar and vector operations or a system in which one
processor is dedicated to string operations (compilation etc.)
and one processor to arithmetic calculations (floating point
arithmetic unit). Each task type has a priority associated
with it, and the number of requests waiting in its queue. These
numbers are maintained in two arrays: priority and count. A
procedure "change-priority" changes the priority of tasks
dynamically depending on the number of requests waiting.
Another procedure "highest-priority" gives the highest
priority task number, whose queue is not empty. The number
of the highest priority task is between 1 to n or n to 2n

depending on whether the flag is set to 1 or 2. If no such
task is found then the procedure "highest-priority" returns λ.
Each processor has an associated monitor processor[i];
i=1,2 which may be the actual hardware of the processor. This
monitor returns its number i in result. "processor" to
interface monitor when it completes the scheduled task. A
complete description is given in expression (4.10). We
maintain separate queues for each type of task using stream
structure ST-REQ.

```
monitor interface (processor, count, priority)
(entry REQUEST do
        ! streams REQUEST and TRIG are changed to
        stream structures!
    ST-REQ ←(for each req in REQUEST do
                streq  ← <"data":req,
                            "selector": req. task>
            return all streq);
    ST-TRIG ← (! TRIG is returned by scheduler code !
                for each trig in TRIG do
                    sttrig ← <"data": trig,
                            "selector": trig >
            return all sttrig);
```

```
RES1 ← (for i from 1 to n do
            ST-REQ1 ← select (ST-REQ, i);
            ST-TRIG1 ← select (ST-TRIG, i);
            RRES1 ← (for each streq1 in ST-REQ1;
                              sttrig1 in ST-TRIG1 do
                        result ←use (processor[·1],
                                streq1)
                              when sttrig1;
                        rresult ← <"data": result,
                                  "selector":i >
                   return all rresult)
            return all RRES1);
    RES2 ← (for i from n to 2n do
            ST-REQ2 ← select (ST-REQ, i);
            ST-TRIG2 ← select (ST-TRIG, i);
            RRES2 ← (for each streq2 in ST-REQ2
                              sttrig2 in ST-TRIG2 do
                        result ← use (processor [2],
                                streq2)
                              when sttrig2;
                        rresult ← <"data": result,
                                  "selector": i>
                   return all rresult)
            return all RRES2);
RESULT ← merge (RES1, RES2);
X ← merge (REQUEST, RESULT);
```

```
! following is scheduler code!
TRIG ← (initial...
        for each x in X do
           if x.type = "req"
           then (if x.task ≤ n
                    then(if status [processor [1]]="free"
                            then trig ← .x.task
                            else new count [x.task] ←
                                    count [x.task] +1;
                                change-priority (priority,
                                            count);
                            trig ← λ)
                    else (if status [processor [2]]="free'
                            then trig ← x.task
                            else new count [x.task] ←
                                    count [x.task] +1;
                                change-priority (priority,
                                            count);
                            trig ← λ))
           else ! it is a done signal from processor
                    monitor!
                (if x."processor"=1
                 then trig ← highest-priority(
                            priority, count,1);
                        status [processor [1]] ←
                        (if trig= λ then "free"
                                    else "busy")
                    else trig ← highest-priority (
                            priority, count,2);
                        status [processor [2]] ←
                        (if trig= λ then "free"
                                    else "busy"))

        return all trig but λ) ;
```

```
                  ! following is code for restoring ordering!
                  rnexts ← create (nexts, RESULT);
                  EX-RES ← (initial flag ← anything
                          for each req in REQUEST do
                              exres ← use (rnexts, req) when flag;
                              new flag ← exres
                              return all exres)
            exit EX-RES)                                        (4.10)
```

Procedures "change-priority" and "highest-priority"
are easy to write and we will not discuss them here.

The monitor interface, if written using dynamic streams
will look something like:

```
      monitor interface (processor, count, priority)
      (entry REQUEST do
              REQ ← (for each req in REQUEST do
                      return all req. task);
              RESULT ← (dswitch DREQ ← REQUEST via REQ;
                              DTRIG ← TRIG via TRIG
                      do
                        RES ← (for each dreq in DREQ;
                                      dtrig in DTRIG do
                            res ← (if dreq. task ≤ n
                                      then use(processor[1],
                                              dreq)...
                                   elseif dreq.task > n
                                          dreq.task ≤ 2n
                                          then use
                                          (processor[2],
                                          dreq)...
                                   else 'error' )
                                  •
                                  •
                                  •                )
                      dmerge RES via REQ)
      exit RESULT)                                             (4.11)
```

In expression (4.10) the stream structures ST-REQ and
ST-TRIG circulate in the loop. However, since input and output
of streams is asynchronous, and ST-REQ and ST-TRIG are not
altered by the loop, all the instantiations of inner loop will
proceed simultaneously. Thus there is no substantial loss
of asynchrony (only that the last instantiation of the inner
loop will start after n units of time). The program in
expression (4.10) uses the select operation on stream structures
whose execution time may be comparable to the execution time
of case statement used in expression (4.11), when the number
of conditions are less (say 2 or 3). However, with a large
number of conditions execution time of the case statement may
be too high, and, it will also be cumbersome to write the
predicates. The program in expression (4.10) does reflect the
steps in the computation more clearly than the program in
expression (4.11).

4.7 Summary

We have discussed stream structures which are useful
in maintaining large and variable number of queues in the
resource management. In fact stream structures can be used
in any place where arrays of streams are required. Furthermore
stream structures require no new Id constructs and/or base
language operators and they are completely user-programmable.

CHAPTER 5

PROGRAMMER DEFINED CONSTRUCTS

In this chapter we propose a mechanism in Id by which
new constructs can be defined. We call it programmer defined
construct. Such a mechanism is useful in abstraction of
operations and in defining one's own language. In Section 4.2
we discuss the syntax for the definition and the use of a
programmer defined construct and the implementation details.
We clarify certain points by discussing several examples in
Section 4.3. Finally, in Section 4.4 we discuss the limitations
of our approach.

5.1 A case for programmer defined constructs

Design and implementation of large and complex software
systems, their subsequent maintenance and modification, and
proving correctness of such systems are facilitated if we
reduce the amount of complexity that must be considered at
any one time. Abstraction, whether it is of operations (events)
or data, provides a way to separate "what" from irrelevent
"how" and thereby reduce the complexity. Data abstraction
[Gut77,, LSAS77,:SWL77, WLS76] has drawn much attention recently.
However, we would also like to view operations in an abstract
way. To some extent, procedures in programming languages
provide a way to the abstraction of operations. A procedure
can be treated as a black box which performs a function and at

the time of its use one need not worry about "how" it does so.

However, procedures are static in their nature, in the sense that they can operate only as a particular expression over different sets of parameter values. A more dynamic facility would be one which specifies only the relationship among the expressions, the actual expressions being supplied at the time of its use [Bac78].

As we mentioned in Chapter 1 that most of the existing programming languages are becoming bulky with the addition of newer and newer constructs to deal with specialized situations or extensions. Still, they remain inherently weak because they can not deal with situations for which they are not designed. This is due to the defects at the most basic level in their design. Their semantics is closely coupled to state transition and they divide the programs into expressions and statements. Whereas the expressions can be combined very easily to form higher level programs, it is difficult to do so with the statements. The result is that conventional languages are forced to have more rigid parts and less variable parts. A more rational approach would be to provide primitive building blocks alongwith a facility which is helpful in building complex and specialized structures using these primitive building blocks. Thus one should be

able to create his own language tailored to his needs
[Bac78].

Bearing the above two points in mind we propose a
mechanism in Id which allows one to define his own constructs.
We call them programmer defined constructs (pdcs in short).
Such mechanisms are provided in LISP [McC62] and RED languages
[Bac73, Bac78]. CLU [LSAS77]and ALPHARD [SWL77]provide an
abstract view of looping mechanisms. A dataflow language
CAJOLE [HOS78], though in a very preliminary development
stage, incorporates the idea of programmer defined constructs.

5.2 Programmer defined constructs in Id

A programmer defined construct in Id is composed of two
parts - its definition and its use. The definition of a pdc
specifies the relationship among the expressions (to be supplied
later at the time of its use) using valid Id schemas. In
defining the relationship, place of an expression is denoted
by a variable enclosed in { } . We will call these variables
exp - variables. For present discussion we assume that only
three Id schemas - block expressions, conditional expressions,
and loop expressions, can be used inside the definition of a
pdc. The use of a pdc specifies the actual expressions and the
values of the arguments. These expressions are substituted in
place of exp variables in the definition of a pdc. This

substitution is performed at run time so the recursive
definitions are allowed. The expression obtained after
substitution is converted to a procedure value which is then
applied to the actual argument values specified in the use of the
pdc. This technique of defining constructs has some similaritie
with the well known conditional assembly of macros used in low
level languages [Str65].

5.2.1 Definition of a pdc:

The syntax for defining a pdc is given informally in
expression (5.1).

$$\underline{construct} \ [\ \{cplist\}] \ [\![\ "\ll construct \ word \gg" \ \{\ll body \gg\}]\!]^n$$
$$\underline{=}(\ll definition \ of \ the \ construct \gg)$$

$$(5.1)$$

$[\![\ ,]\!]$, $\ll$, $\gg$ are metasymbols. $[\![\qquad]\!]^n$ denotes n
occurances of the string enclosed in $[\![\qquad]\!]$ and for our purpose
$n \geq 1$. The formal syntax of construct definition is given in
Figure 5.1.

The string $[\![\ " \ll construct \ word \gg"\{\ll body \gg\}]\!]^n$ specifies
how the pdc will be written when it is used in a program. The
exp-variable { cplist } denotes a list of variables which will
be supplied by an use of the pdc. We want to emphasize here
that only valid Id expressions, and not Id statements, can be
substituted in place of exp-variables i.e. variables enclosed

≪ construct definition≫ ::= construct [≪exp-variable≫]

≪ usage form ≫= (≪construct def ≫)

≪ exp-variable≫ ::= {≪ identifier ≫}

≪ usage form≫ ::= ≪ construct word-body ≫≪usage form≫ []

≪ construct word-body ≫

≪ construct word-body≫ ::= ≪ construct word ≫≪exp-variable≫

≪construct word≫ ::= "≪identifier≫"

≪ construct def≫ ::= ≪ valid extended bclu Id expression≫

≪valid extended bclu Id expression ≫::= valid Id block, conditio-
nal or loop expression or
a construct use with
≪ extended Id variables ≫

≪extended Id variables ≫::= ≪Id variable ≫ [] ≪ exp-variable ≫

≪ Id variable≫ ::= ≪ identifier ≫

≪ identifier≫ ::= string of English alphabets and special symbols
excluding null string.

Figure 5.1 Syntax of the definition of a pdc.

in { }. As an example, we give definition of a case expression
using conditional expression in expression (5.2).

$$\underline{construct} \; [\; \{cplist\} \;] \; "case \; | "\{pred \; 1 \; \}" \; \Rightarrow " \; \{ \; body \; 1 \; \}$$
$$" \; "| \; "\{pred \; 2 \; \} \; " \; => " \; \{ \; body \; 2 \; \}$$

$$=(\underline{if} \; \{pred \; 1\} \; \underline{then} \; \{body \; 1 \; \}$$
$$\underline{elseif} \; \{ \; pred \; 2 \; \} \; \underline{then} \; \{body \; 2\}$$
$$\underline{else} \qquad) \qquad\qquad (5.2)$$

Expression (5.2) does not bring out all the points which
are important, however, it is only intended to give a flavour
of syntax. Other points will be made clearer in later sections.

5.2.2 Use of a pdc:

The syntax for the use of a pdc can be explained
informally by expression (5.2).

$$[\; \ll list \gg \;] [\!] \; " \; \ll construct \; word \; \gg " \; \ll exp \; \gg]\!]^n$$
$$\underline{using} \; [\ll \; argument \; list \; \gg \;] \qquad\qquad (5.3)$$

Formal synatx is given in Figure 5.2. 'exp'denotes any
valid Id expression or a list of expressions. 'list' specifies
the variables used in these expressions. Actual values of
these variables should be supplied from outside. We have
introduced a new reserved word, using. The list following
using i.e.'argument list' specifies the actual values for

« construct use » ::= [« list »]« use form »

                        <u>using</u> [« argument list »]

« list » ::= « identifier »`, « list » ‖ « identifier »

« use form » ::= « construct word use »« use form » ‖

                   « construct word use »

« construct word use » ::= « construct word »« valid Id exp+const »

« valid Id expression+const » ::= « valid Id expression » ‖

                              « construct use »

« argument list » ::= « valid Id expression » , « argument list »

                 ‖ « valid Id expression »

« construct word » ::= "« identifier » "

« valid Id expression » ::= any valid Id expression

« identifier » :.= string of English alphabets and special symbols

                excluding null string

Figure 5.2 Syntax of the use of a pdc.

variables listed in 'list'. The correspondence is by position
(easiest, though other formulations can be specified).
'Argument list' may contain valid Id expressions as the values
for the variables listed in 'list', in which case expressions
are first evaluated and then the evaluated values are passed.
using also specifies the scope of the pdc.

Expression (5.4) shows the use of the pdc defined
in expression (5.2).

$$z \leftarrow (\ [x,y,a,b,i,n]\ "case\ |"\ i< n"=>"\ x+2*a$$
$$"|"\ i= n"=>"\ y+2*b*a$$
$$\underline{using}\ [x,y,e,f,i,10]\ )\hspace{3cm}(5.4)$$

Here we would like to point out the difference between
x in 'list' and x in 'argument list'. x in 'list' denotes
a variable which will be used inside the pdc, whereas, x in
'argument list' denotes the variable (i.e., the line in base
language graph) outside the pdc. using specifies an inter-
connection between them. The facility of using can be made
general enough so that it can be used to avoid writing
statements in many cases.

5.2.3 Implementation of a pdc:

Like a procedure value, the definition of a pdc is
translated as constant function which produces a new type of

value called 'pdc'. The value of the type pdc has the following internal representation:

< name: pdc name,

   usage form: the string enclosed in ⟦   ⟧ in expression

            (5.1)

   definition: definition of the pdc >

pdc name is obtained by concatenating all the construct words. The translation of expression (5.2) is shown in Figure 5.3.

The use of a pdc is translated as a function <u>evalc</u>. The inputs to the function <u>evalc</u> are:

1. pdc definition value.
2. A structure containing 'list' and the actual expressions in the form of strings. For future reference this structure will be called <u>expvalue</u>.
3 The actual values of arguments as given in 'argument list'.

The function <u>evalc</u> evaluates the pdc and its outputs are the outputs of the pdc expression. Figure 5.4 shows the translation of expression (5.4).

The function <u>evalc</u> is not implemented as a primitive operator. It is composed of two operators - substitute, and apply. Figure 5.5 shows the internal structure of <u>evalc</u> and one may refer to it to understand the functions of two operators, which are discussed below.
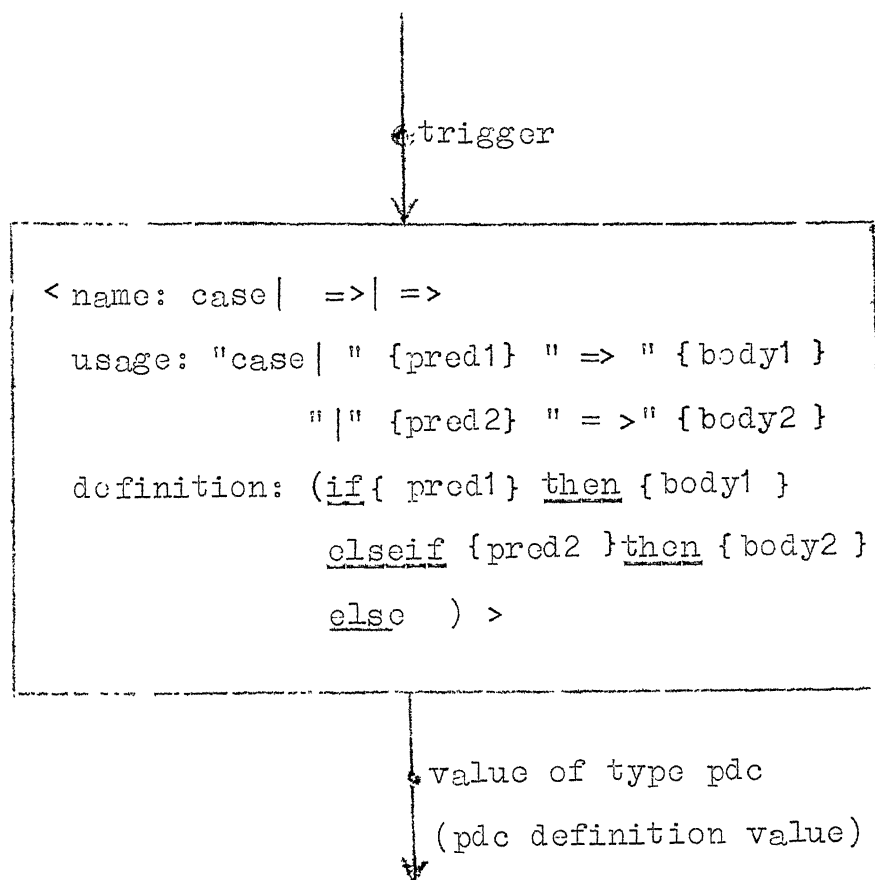
↓

↓trigger

↓

< name: case| =>| =>

  usage: "case| " {pred1} " => " {body1 }

          "|" {pred2} " = >" {body2 }

  definition: (if{ pred1} then {body1 }

           elseif {pred2 }then {body2 }

           else) >

↓value of type pdc

  (pdc definition value)

↓

Figure 5.3   Translation of the definition of
pdc of expression (5.2).
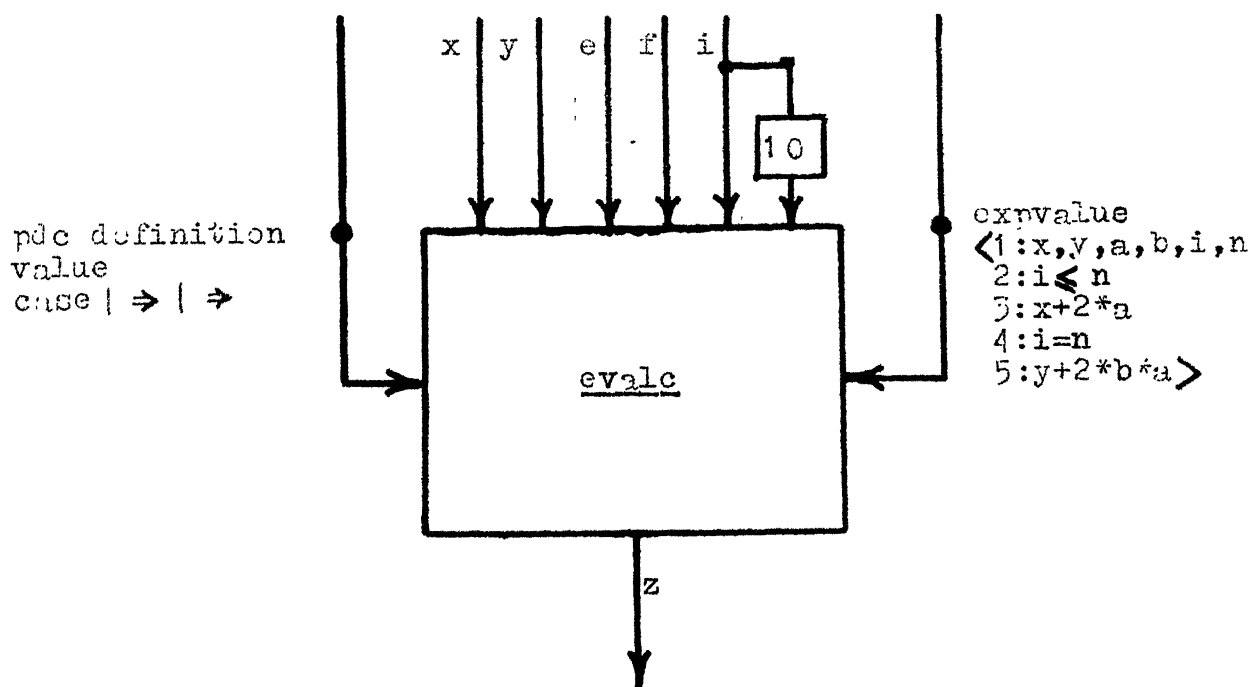
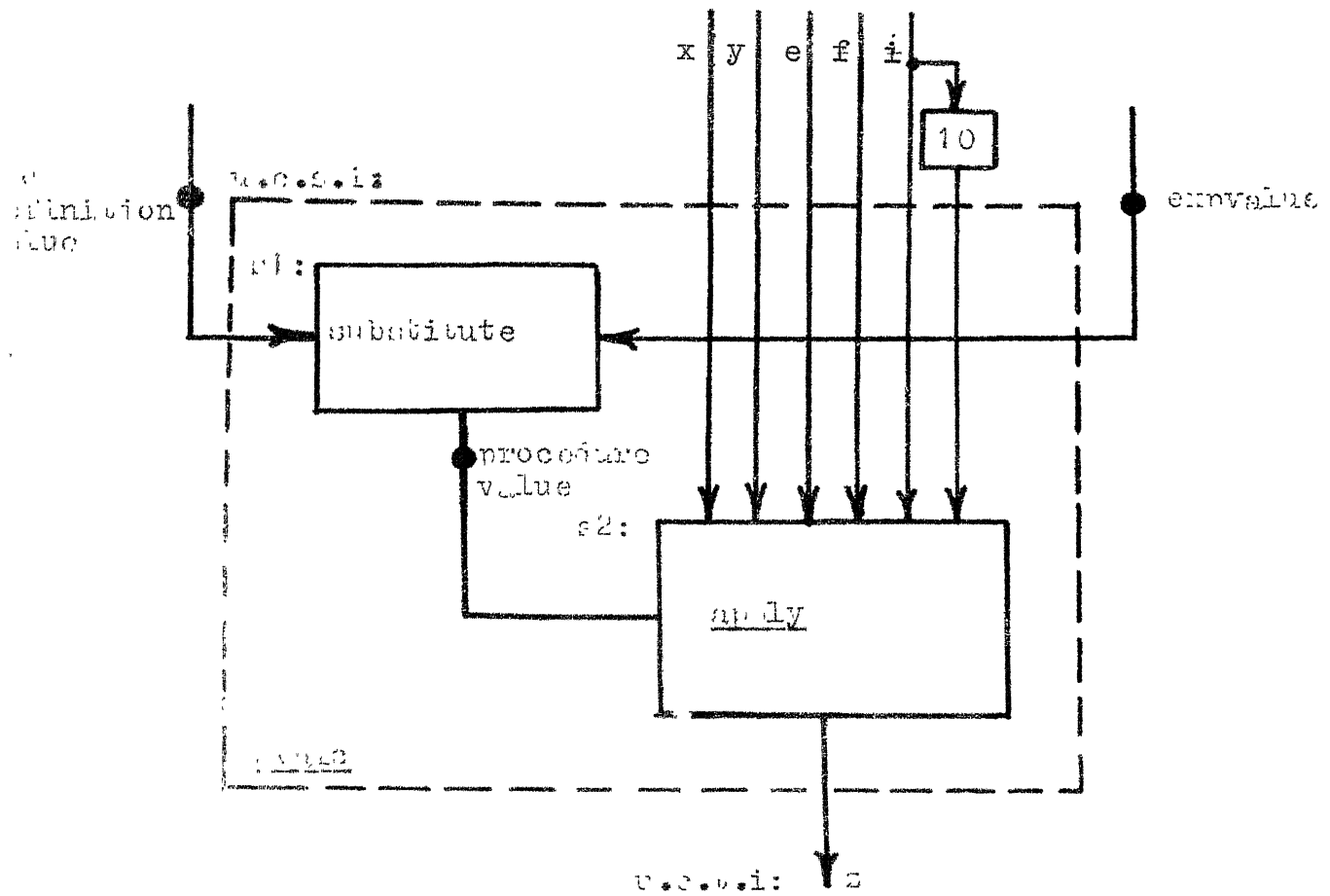Figure 5.4   Translation of the use of a pdc
(expression (5.4)).

Figure 5.5 Schematic of evals.

a. <u>substitute</u>:

It performs two functions - it substitutes the actual expressions in place of exp-variables and then it creates a new procedure value using substituted definition. If the data structure of Id expressions is represented in the form of structure or string values then no new operator except a coercion function from structure or string to procedure is required. The created procedure value is passed to the <u>apply</u> operator. The actual expressions are obtained from structure expvalue. The correspondence between actual expressions and exp-variables is decided using usage part of pdc definition value and is by position i.e. expvalue.1 corresponds to {cplist} and so on. Name of the created procedure value is the first construct word and formal parameter list of the procedure value is the actual list corresponding to { cplist }. To allow for recursive definition of a pdc, pdc definition value is passed to the procedure value as a "freezed" argument.

$$u.c.s_1.i \quad -- \text{ input: port 1 (pdc definition value)} = c_v$$
$$\text{port 2} = \text{expvalue}$$
$$\text{output} = \ll \text{create proc (subst}(c_v, \text{expvalue}))\gg,$$
$$< u.c.s_2.i >>$$

<u>subst</u> performs string substitution and it can be expressed as an Id procedure. However, <u>createproc</u> converts

the substituted definition to a procedure value and cannot be expressed in Id. The procedure value passed to <u>apply</u> operator at the execution time of expression (5.4) is given by q in expression (5.5).

$$p \leftarrow \underline{procedure} \ case \ (construct, \ x,y,a,b,i,n)$$
$$(\underline{if} \ i < n \ \underline{then} \ x+2*a$$
$$\underline{elseif} \ i = n \ \underline{then} \ y+2*b*a$$
$$\underline{else} \qquad);$$

$$q \leftarrow \underline{compose} \ (p, < \ case \ | \ => | => \ ,,,,,, > \ ) \qquad (5.5)$$

b. <u>apply</u>:

It takes the procedure value which is passed to it by the operator substitute and applies it to the actual arguments. The results are passed to the program segment where construct is used. This operator is discussed in some detail in Section 2.3.

5.3 <u>Some examples</u>

In this section we will discuss some examples of pdcs to illustrate some of the points relevant to their definition and their use.

a. <u>A while loop</u>:

Expression (5.6) gives recursive definition of a pdc which is equivalent to the <u>while</u> loop in Id. Expression (5.7) shows its use.

construct [{ cplist}] "while" { predicate} "do"

$$\{ body \}$$
$$\equiv (\underline{if} \{ predicate \} \underline{then} [\{ cplist \}]$$
$$\text{"while"} \{predicate\} \text{"do"}$$
$$\{body\}$$
$$\underline{using} [\{body\}]$$
$$\underline{else} \{cplist\}) \qquad (5.6)$$

[sum, x,i,n] "while" $i \leq n$ "do"
$$sum +x, x, i+1, n$$
$\underline{using}$ [sumo, xo,1,10] $\qquad\qquad$ (5.7)

Values returned by expression (5.7) are the final values
of the expressions sum+x, x, i+1, n. This example brings out
a restriction i.e. use of any recursively defined pdc should
return the values for all the variables specified in its 'list'.

b. A for-while loop:

We implement a for-while loop using the pdc mechanism
and the for each-while loop. The implementation is based on
the translation of for-while loop into a for each-while loop
as discussed in Chapter 3. The definition of the construct
is given in expression (5.8).

```
construct [ {cplist} ]"for"{var}  "from" { lower limit }
                  "to" {upper limit}"by" { step }
                  "while" { pred. }        "do"
                        {body }
                  "return" { explist }
     = ('local'.{explist},  S' ←(initial{cplist }←{cplist }
                        for each {var}in I
                        while {pred}∧{var}≠ ε do
                           new({ cplist}) ←{ body}
                           return{explist},all true);
          S← cons (true, S' );
          I← (initial j ←{lower limit }
              for each s in S do
                 if j≤{ upper limit}then new j ← j+{step};
                                      j' ← j
                                   else new j ←ε ;
                                      j' ← ε
              return all j' );
          return 'local'. {explist }))          (5.8)
```

The use of the above construct is shown in expression
(5.9).

$$[\text{sum}, \, p,q,r,n,a \,] \text{ "for" } i \text{ "from" } p \text{ "to" } q \text{ "by" } r$$

$$\text{"while" } \text{sum} < n \text{ "do"}$$

$$\text{sum}+i*a,p,q,r,n,a$$

$$\text{"return" } 3*\text{sum}$$

$$\underline{\text{using}}[\text{ sumo}, \, 1,10,2,s,b \,] \qquad\qquad (5.9)$$

We used the reserved word <u>new</u> in a rather different manner in expression (5.8). If we assume that{ cplist}$\equiv$ a,b,c then at the time of substitution <u>new</u> ({ cplist}) will be converted to <u>new</u> a, <u>new</u> b, <u>new</u> c. We have also introduced a new way of generating variable names. 'local'.{ explist} means that string 'local' is concatenated with all the strings occuring in {explist} and new variable names are formed. As an example, if {explist} $\equiv$ x,x+y then

$$\underline{\text{'local'}} \cdot \{ \text{explist} \} \equiv \text{localx,localx+y}.$$

localx+y is the name of a variable. The need to do this stems from the single assignment property of Id.

c. <u>A for loop that returns streams:</u>

Expression (5.10) gives the definition of a pdc which is equivalent to the Id <u>for</u> loop with <u>return</u> <u>all</u> construct. Expression (5.11) shows how it can be used in a program.

$$\underline{\text{construct}} \ [\{\text{cplist }\}] \ \text{"for"}\{\text{var}\} \ \text{"from"} \ \{\text{lower`limit}\}$$
$$\text{"to"}\{\text{ upper limit}\}\text{"do"}$$
$$\{\text{body}\}$$
$$\text{"return"}\{\text{ explist 1 }\}\text{"all"} \ \{\text{explist 2}\}$$
$$\equiv (\underline{\text{initial}}\{\text{cplist }\}\leftarrow\{\text{cplist}\}; \{\text{ var }\}\leftarrow\{\text{lower limit }\}$$
$$\underline{\text{while}} \ \{\text{var }\}\leq\{\text{upper limit}\} \ \underline{\text{do}}$$
$$\underline{\text{new}}(\{\text{cplist}\}) \leftarrow \{\text{body}\};$$
$$\underline{\text{new}} \ \{\text{var}\} \leftarrow\{\text{var}\}+1$$
$$\underline{\text{return}} \ \{\text{explist 1 }\}, \ \underline{\text{all}} \ (\{\text{explist 2}\}))$$

$$(5.10)$$

$$[\text{x,y,p,n}] \ \text{"for"} \ i \ \text{"from"} \ p \ \text{"to"} \ n \ \text{"do"}$$
$$f(x,y,i), \ f'(x,y,i), \ p,n$$
$$\text{"return"} \ x,y \ \text{"all"} \ g(x,y,i),g'(x,y,i)$$
$$\underline{\text{using}} \ [\text{xo,yo,1,10 }] \qquad (5.11)$$

In this example we used a <u>while</u> loop to define a <u>for</u> loop. In expression (5.10) the use of <u>all</u> is similar to the use of <u>new</u> in expression (5.8).

d. <u>A sequential loop construct:</u>

We now implement a sequential <u>for each</u> loop construct as a pdc. Our implementation is based on translation given in Chapter 3 (expression (3.5)). The definition of the pdc is given in expression (5.12) and its use in expression (5.13). This example brings out some of the limitations of our approach.

construct [{cplist }]"for each"{ var1} "in"{stream1 }","

{ var2} "in"{stream2 }"do"

{ body }

"return"{ explist }

$\equiv$ (I',J' $\leftarrow$ (for each i in {stream1} do

I',J' $\leftarrow$ (for each j in {stream2 }do

. return all i, all j)

return all I', all J')

return (initial {cplist} $\leftarrow$ {cplist}

for each{ var1} in I';{var2}in J' do

new ({ cplist}) $\leftarrow${body }

return{ explist}))   (5.12)

[x,y,I,J]"for each" i "in" I "," j "in" J "do"

f(x,i,j), f(y,i,j)

"return" x,y

using [xo,yo,I,J]   (5.13)

Since the values of the streams I and J should be
supplied from outside, they occur in the 'list' in expression
(5.13). At the time of substitution,{ cplist} $\equiv$ x,y,I,J and
thus statement new ({ cplist}) $\leftarrow$ { body }will be translated as

new x, new y, new I, new J $\leftarrow$ { body }.

This will result in circulation of streams I and J in the

second loop of expression (5.12). Circulation of streams is to be avoided for the obvious reasons of efficiency. In fact in this case second loop never uses the streams I and J. An optimising compiler may detect this fact and treat I and J as dead variables.

A way to avoid such a circulation of streams would be to define a deletion operation on { cplist }. If we denote the deletion operation by – then we can write

new ({ cplist} – {stream1 } – {stream2 }) ←{ body }

which, when translated at the substitution time, would result in

new x, new y ← { body}.

Then one can also think of defining a complementary operation addition on { cplist }.

5.4 Limitations of our approach

We pointed out a limitation of our approach in example (d) in Section 5.3 and suggested a solution. The limitation arose from our need to distinguish between circulating and uncirculating variables in a loop expression for the reasons of efficiency. Sometimes a programmer may want to circulate a stream to obtain desired results. Our proposed solution is neither elegant nor general enough.

It also increases the complexity of 'subst' in the implementation. A general solution to distinguish circulating variables from uncirculating variables will require a complete analysis of the program.

Second limitation or restriction is pointed out in example (a) in Section 5.3, i.e. a recursively defined pdc should return values for all the variables in 'list'.

Finally we would like to point out that our approach is not dynamic enough. Consider the definition of a case expression as given in expression (5.2). This expression can deal with only two cases. We have to define separate case expressions to deal with three cases, four cases and so on. A general case expression dealing with any number of cases cannot be defined in our model because a pdc is ultimately converted to a procedure and thus cannot model dynamicness in its definition itself. Conversion of a pdc to a procedure also reduces the interaction between the use of the pdc and the program where it is being used.

5.5 Summary

In this chapter we have discussed the definition, the use, and the implementation of programmer defined constructs in Id. Programmer defined constructs are useful in abstraction

of operations and in defining one's own language. The
definition of a pdc specifies the relationship among
expressions in terms of Id schemas and dummy expressions.
The actual expressions are supplied by the use of a pdc.
To bring out certain important points and limitations
of our approach we have discussed several examples.

CHAPTER 6

CONCLUSIONS

In this thesis we have proposed certain extensions to the high level data flow language Id so that its basic mechanisms can be fully exploited. It is evident from the discussions in Chapter 3 and 4 that some of these extensions, can be incorporated without any major alteration in the set of base language operators. An alternate translation of the _for_ loop and the _for each-while_ loop as discussed in Chapter 3, enables us to incorporate sequential and mixed looping constructs and to enumerate the elements of a pdt in a controlled fashion. Similarly in Chapter 4 a slight modification of monitors enabled us to exploit the stream structures in the resource management problems. This points to the fact that the basic mechanisms in Id are powerful enough and their full potential is yet to be realized . In Chapter 5 programmer defined constructs were proposed as an addition to the basic mechanisms in Id. In fact the pdcs can be used to implement most of the constructs discussed in Chapter 3 and thus effectively reduce the size of the language.

Many ideas from Id and this thesis can also be extended to the conventional languages. The structure of the looping constructs in Id explicitly specifies the initialization

of the loop variables, and, an Id loop can terminate only
when the associated predicate turns false. Such a structure
of loops in a conventional language will facilitate program
verification. An equivalent of parallel <u>for</u> <u>each-while</u>
loop construct alongwith the generators will be able to
model nearly all looping constructs in a conventional
programming language. Recent languages such as ALPHARD have
adopted such a view of loop constructs.

Another idea which can be extended to conventional
programming languages is that of programmer defined constructs
type. Using the conventions of Chapter 5, below we briefly
outline how pdcs can be incorporated in the conventional
languages:

Whenever a construct definition is encountered, it is
entered in a structure, say <u>environment</u>. The user (always)
specifies the name of the environment he will be using during
the execution of his program. Initially <u>environment</u> may
be an empty structure. Whenever a construct use is encountered
it is translated into two statements:

1. a call to a system procedure <u>evalc</u> with the name
   of the construct and a structure containing actual
   expressions,
2. a call to the procedure, whose name is the first
   construct word, with the arguments specified in the
   argument list of the construct use.

The system procedure evalc substitutes the actual expressions in the construct definition, creates a procedure from the substituted definition, and then calls the compiler to translate the created procedure. A dynamic linking and loading facility will make the procedure available to the program. For incorporation of the mechanism in the languages which do not view the procedures as functions, the {cplist} needs to be extended to include the variables whose values are being returned by the construct. The arguments are transferred using 'call by value'.

During the course of this work we recognized many areas which are still unexplored or partially explored. Our discussion on pdcs is certainly not the last word on the subject. There are certain limitations in the proposed approach and it would be worthwhile to investigate how these limitations can be removed from the present frame work. Another area of interest is the specification of a minimal set of Id constructs which alongwith the facility of pdcs are powerful enough to model any programming problem. In specifying such a minimal set, the efficiency consideration should not be unduly compromised. Also the constructs in the minimal set should not be at such a primitive level that one has to deal with the base language.

Recent Turing lecture by J. Backus [Bac78] has brought functional forms of   programming languages into vogue. At this stage we speculate that if the unravelling interpreter can be made to execute functional programs efficiently, then the resulting system will be able to do away with most of the objections against conventional systems (both software and hardware) and can emerge as a powerful next generation system.

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